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MARGINAL VALUE OF STREAMFLOW IN COLORADO RIVER BASIN UNDER ALTERNATIVE RESERVOIR MANAGEMENT STRATEGIES

Benjamin L. Harding & Taiye Sangoyomi

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Benjamin L Harding and Taiye Sangoyomi
Hydrosphere Resource Consultants
Boulder, Colorado

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Glen Canyon Dam Operational Study

August, 1995

1. INTRODUCTION

1.1. Background

The impact of the operation of Glen Canyon Dam on downstream environmental resources, particularly within the Glen and Grand Canyons, has been of major public concern. These concerns have been expressed since Lake Powell, formed behind the dam, filled for the first time in 1980. The main concerns about the dam operations are the greater fluctuating releases, and the higher frequency of flood or excessive releases from the dam. These releases impact the vegetation, fish, sediment transport, wildlife habitat, endangered species, and archaeological sites within Glen and Grand Canyons.

Several environmental impact assessments have been conducted to evaluate downstream impacts of the dam, and to determine if operational changes at the dam could mitigate those impacts. In December of 1982, the Secretary of the Interior directed the Bureau of Reclamation to initiate a multi-agency study. This study was intended to investigate the impact of current dam operations on the existing environmental and recreational resources in the Glen and Grand Canyon National Parks, and to determine whether modifications made to the dam operations could reduce those impacts.

Several reports were issued from that study including the Glen Canyon Environmental Studies (GCES) Final Report (USDOI 1988). Agencies involved in the study include the Western Area Power Administration (WAPA), the Fish and Wildlife Service (FWS), the National Park Service (NPS), and the Bureau of Reclamation (BOR). The GCES stated that two aspects of current operations, flood releases and fluctuating releases, have substantial adverse effects on downstream resources. Flood releases (defined in the study to be any release greater than the powerplant hydraulic capacity) were found to occur in about one in four years. The report recommended that flood releases should be avoided until a "tolerable frequency" can be defined. The GCES, however, reported no quantification of the impact of changes in operation at Glen Canyon Dam on the frequency and magnitude of flood flows.

In 1986, the Water Science and Technology Board in the Department of Interior asked the National Research Council to conduct a review of the GCES and to provide advice on alternative operation schemes at Glen Canyon Dam. The council formed the Committee to Review the Glen Canyon Environmental Studies. The committee presented its findings in 1987 (NRC, 1987). The committee noted that the GCES had not analyzed the effect on flood releases of changes in operation at Glen Canyon. This, according to the committee, was a serious deficiency in the GCES. The committee noted that the analysis required to examine the effect of operational changes on flood frequency and magnitude was well within the scope and resources of the GCES.

A review of the GCES was also carried out by the Executive Review Committee (ERC), and presented in the GCES Executive Review Committee Final Report of May 1988. Even though three of the four co-operating agencies (BOR, FWS, and NPS) recommended that flood flows be reduced to the greatest extent possible, and the NPS indicated that more information was required on the effect of operational changes on flood control frequency, the ERC report did not recommend that future studies be carried out to examine the effect of operational changes on flood frequency and magnitude. The ERC only recommended that future studies be carried out on the effects of fluctuating releases on downstream resources.

Hence, the Draft Environmental Impact Statement (EIS) on the operation of Glen Canyon Dam, which was released in 1993 (USDOI, 1993), did not address the impact of operational changes on flood frequency. The nine scenarios considered in the 1993 report were all focused on the effect of fluctuating releases on environmental resources. It is therefore important that a study be carried out to provide information necessary to allow for evaluation of how operational changes at Glen Canyon Dam would influence flood or excessive releases below the dam.

1.2. Objective

The primary objective of this study is to assess how changes in Glen Canyon Dam operations would influence the magnitude and frequency of floods or excessive flows below the dam. A flood release was defined as in the GCES to be any release greater than Glen Canyon Dam's powerplant hydraulic capacity, which is 33,200 cfs, that is discharged through the river outlet works and/or spillways. Flood or excessive releases are used interchangeably in this report. The study also examined how operational changes at Glen Canyon Dam would influence the frequency of monthly flows below Upper Basin Reservoirs (Flaming Gorge was selected for this), and below Lake Mead, formed by the Hoover Dam. In addition, the effect of operational changes at Glen Canyon Dam on water availability for beneficial use in the basin, hydropower production at Glen Canyon Dam, and salinity below Lake Mead were assessed.

1.3. Methodology

Five flood operational policies at Glen Canyon Dam were considered for this study. Four of these relate to the creation and timing of different sizes of additional flood space in Lake Powell. These are: (a) an operating policy that prescribes no exclusive flood control space in Lake Powell; (b) the current operating policy that prescribes a 0.5 maf exclusive flood storage space in Lake Powell by July 1; (c) an operating policy that prescribes an additional 0.5 maf exclusive storage space beyond that in the current operating plan; and (d) an operating policy that prescribes an additional 1.0 maf exclusive storage space beyond that in the current operating policy. The fifth operational policy relates to the proposed structural measure to increase Lake Powell's flood pool (USDOI, 1993). The structural measure is proposed to raise the height of the four spillway gates 4.5 feet to elevation 3704.5 feet, thereby increasing the flood pool by 0.75 maf over the current flood operating policy.

To assess the effects of the five Glen Canyon Dam operational plans on the frequency of excessive monthly flows below the dam and on the frequencies of the other variables enumerated above, Hydrosphere's Colorado River Model (CRM) was used to simulate the system. The simulations employed three different depletion levels for years 1991, 2010, and 2030, and a synthetic streamflow trace covering a 1,400-year period. The CRM simulates water allocation, reservoir operations, evaporation, hydropower, and salinity within the Colorado River Basin using a monthly time step.

1.4. Limitations

The limitations of using a model with a monthly time step to study the frequencies and magnitudes of floods is recognized. A model with a monthly time step is unlikely to capture all information from a flood study because floods occur over a range of time steps some of which are smaller than one month, e.g., flood durations could be on the order of days, hours, or even minutes (flash floods).

Frequent flooding with short flood durations will typically occur at streamflow locations with little or no influence from an upstream reservoir. However, at a streamflow location with considerable influence from an upstream reservoir, the floods will be fewer and have longer durations because of the modulating effect of the upstream reservoir operations on river discharges. Since the location of the proposed study is below Glen Canyon Dam--which created Lake Powell, a reservoir with a storage capacity of 24.322 maf--reservoir operations are expected to considerably modulate the river discharges to remove sharp spikes from the outflow hydrology, and to reduce the variation of the daily flow about the mean monthly flow. Hence, flood flows below Glen Canyon Dam are expected to last for several days; a model with a monthly time step should, therefore, be able to quantify flood flow impacts within reasonable limits.

The above hypothesis is investigated in Appendix A, where the daily and monthly recorded flows below Glen Canyon Dam were analyzed from October 1921 to September 1991--a period spanning intervals before Glen Canyon Dam was built (1921-62), after the dam was built and Lake Powell was filling (1963-80), and after Lake Powell filled for the first time (1981-91). The analyses indicate that during the pre-dam period, a monthly model will "see" a flood (defined as flows above 33,200 cfs) 51% of the time that a daily model "sees" the same flood. This percentage, however, increases to 82% after Lake Powell filled for the first time.

1.5. Report Outline

The remainder of this report is organized as follows: Section 2 describes the physical and institutional setting within which Glen Canyon Dam exists; Section 3 describes the simulation model employed for the study; Section 4 details the operational schemes that were evaluated for use at Glen Canyon Dam; Section 5 describes the analyses carried out with the simulation model; Section 6 presents the results and discussions; and Section 7 contains the conclusions from the study. Five appendices also accompany this report. Appendix A contains the analysis of the adequacy of using a model with a monthly time step for flood control studies, and Appendix B contains a listing of the depletion points in the CRM. Appendices C, D and E, contain graphs of output results from the CRM, with depletions at year- 1991, 2010 and 2030 levels, respectively.

2. PHYSICAL AND INSTITUTIONAL SETTING

The Colorado River system comprises of several reservoirs and water resources projects that are operated in an integrated manner. The operation of the system is carried out following a unique set of institutional constraints that has evolved over time, comprised of judicial, statutory, contractual and administrative decisions. Glen Canyon Dam operates within this setting. Hence, operations at the dam cannot be considered in isolation, but must be considered within the physical and institutional setting of the Colorado River Basin. Therefore, an understanding of the physical and institutional constraints on

the operations at Glen Canyon Dam is necessary. This section provides an overview of the physical and institutional setting within the basin required for obtaining such an understanding.

2.1. Physical System

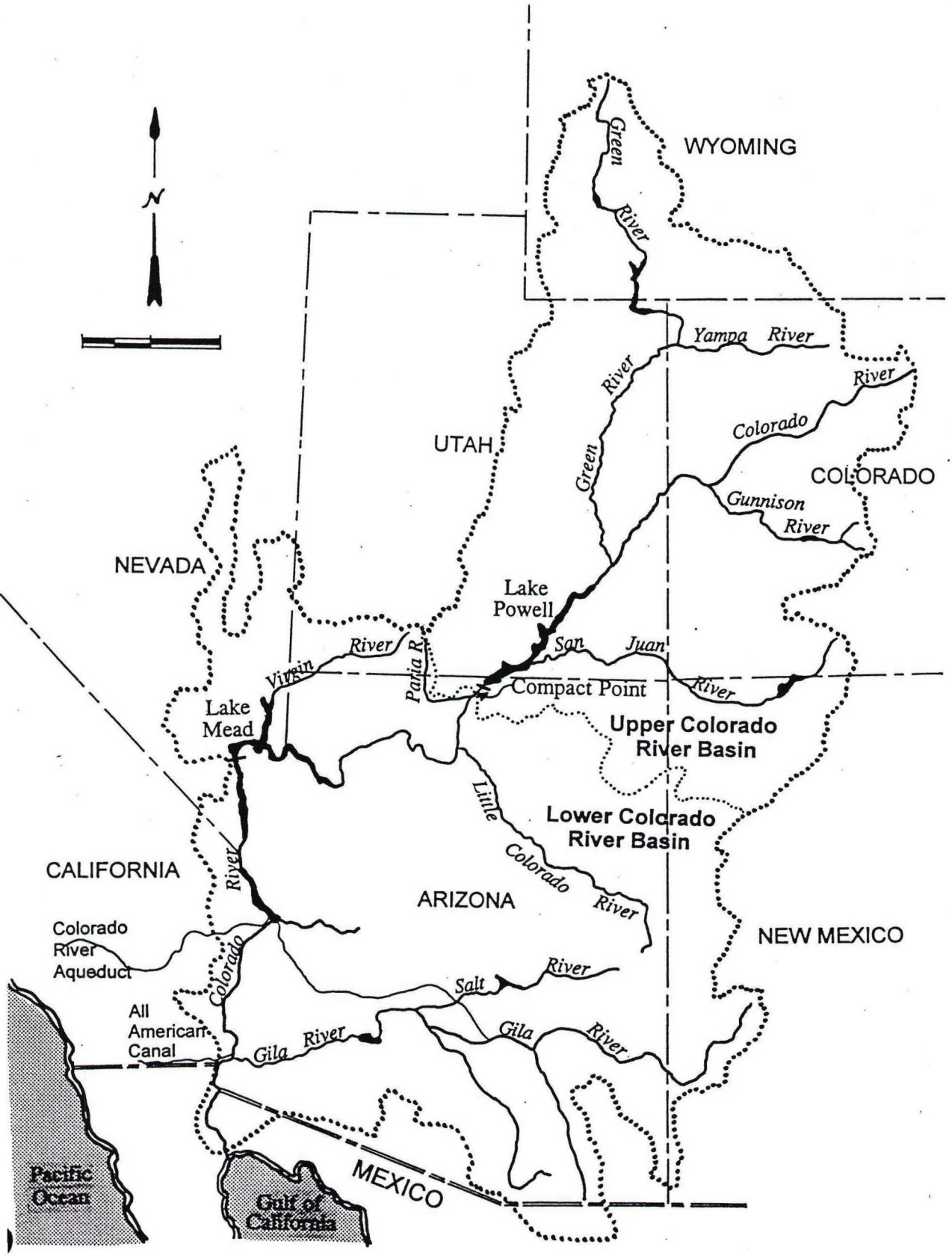
The Colorado River basin drains approximately 243,000 square miles contained within the states of Colorado, Wyoming, Utah, New Mexico, Nevada, Arizona, California, and parts of the Mexican states of Baja, California and Sonora. The river is highly regulated by a total reservoir storage capacity approximately equal to four times the river's average annual flow. Figure 1 shows the geographical extent of the Colorado River basin, the seven basin states, and the major rivers and reservoirs in the basin.

The basin is divided both geographically and politically at Lee Ferry, just downstream of the point where the river crosses the Arizona-Utah border. The Upper Basin includes lands in the states of Colorado, New Mexico, Utah, and Wyoming, and is the principal source of inflow into the Colorado River system. The Lower Basin includes lands in the states of Arizona, California, Nevada and New Mexico. A lesser amount of inflow occurs in the Lower Basin, principally via the Little Colorado, Virgin, Bill Williams and Gila Rivers.

The natural flows in the basin are highly irregular in occurrence. While the virgin flow at Lee Ferry has averaged 15.1 million acre-feet annually over its measured period of record, natural flows in excess of 23 million acre-feet and less than 7 million acre-feet annually have been recorded. Over 70% of the annual natural flow occurs in the months of May, June, and July. Flows have been recorded for less than 100 years at most points on the river. Inflows at 29 locations are modeled in the simulation model described in Section 3. The inflow points are indicated on Figure 1.

Many reservoirs alter the natural flow of the Colorado River. Fourteen of these reservoirs are modeled, and they contain a total active capacity of 61,375,000 acre-feet. The two principal reservoirs, Lake Powell and Lake Mead, provide over 50 million acre-feet (maf) of storage. The other reservoirs modeled in the simulation model are Fontenelle, Flaming Gorge, Starvation, Taylor Park, Blue Mesa, Morrow Point, Crystal, Ridgway, McPhee, Navajo, Mohave, and Havasu.

Water is diverted from the river at hundreds of relatively small diversion points in the Upper Basin. The Lower Basin diversions tend to be larger and considerably fewer in number. Major diversion structures in the Lower Basin include the Colorado River Aqueduct which delivers water to the Los Angeles basin, the Havasu Pumping Plant/Central Arizona Project Canal which supplies the Central Arizona Project, the Colorado River Indian Reservation Main Canal in Arizona's Parker Valley, the Palo Verde Canal which diverts water to the Palo Verde Irrigation District of California, the All American Canal System bringing water to the Imperial and Coachella Valleys of California and the Yuma Project in California and Arizona, and the Gila Main Gravity Canal which serves the Gila project in Arizona. Below the international boundary, Morelos Dam diverts water for irrigation in Sonora, Mexico.


N
WYOMING
Green River
Yampa River
Green River
Colorado River
UTAH
COLORADO
Gunnison River
NEVADA
Lake Powell
San Juan River
Virgin River
Paria R.
Compact Point
Lake Mead
Upper Colorado River Basin
Lower Colorado River Basin
Little Colorado River
CALIFORNIA
Colorado River
ARIZONA
NEW MEXICO
Colorado River Aqueduct
Salt River
All American Canal
Gila River
Gila River
MEXICO
Pacific Ocean
Gulf of California

The Colorado River is already one of the most fully developed in the world. However, additional storage and diversion projects are being planned and actively pursued throughout the basin. The U. S. Department of Interior, Bureau of Reclamation, as the principal entity responsible for operation and administration of the river, maintains a list of future water supply projects and their depletions anticipated for implementation in each of the basin states. Current water development plans of the individual states generally anticipate full development of their legal entitlements by the year 2040.

2.2. Institutional Setting

The allocation of water within the Colorado River basin is constrained within an institutional setting that has evolved from judicial, statutory, contractual and administrative decisions. These decisions are collectively known as the Law of the River. They have, for the most part, been generally fashioned after the prior appropriation doctrine applied in the western states. A summary of the important resolutions from these decisions from the standpoint of this study are set out in the following paragraphs (Meyers, 1966; Nathanson, 1978).

The Colorado River Compact of 1922 apportioned the flow of the river between the Upper Basin States (Arizona, Colorado, New Mexico, Utah, and Wyoming) and the Lower Basin States (Arizona, California, and Nevada). It applied the principle of equitable division in recognition of the likelihood that application of the doctrine of prior appropriation would allocate most of the river's water to the more rapidly developing states of the Lower Basin. The compact required that the Upper Basin deliver a 10-year moving average of 7.5 million acre-feet at Lee Ferry to the Lower Basin.

The California Limitation Act of 1929 limited the annual consumptive use of California from the Colorado River to 4.4 million acre-feet per year to be taken from the 7.5 million acre-feet per year apportioned to the Lower Basin, plus not more than one-half of any surplus waters unapportioned by the 1922 Compact.

The Boulder Canyon Project Act of 1928 authorized the Lower Basin states to apportion the waters of the Lower Basin as follows: California 4.4 million acre-feet, Arizona 2.8 million acre-feet, and Nevada 0.3 million acre-feet, though such an agreement was not executed at that time.

The Mexican Treaty of 1944 guaranteed a minimum of 1.5 million acre-feet per year to Mexico. If surplus supplies exist in any year, presumably to be determined by the Secretary of the Interior, the treaty allows deliveries to Mexico to be expanded by 200,000 acre-feet. The Treaty also allows for a reduction of deliveries in the event of an "extraordinary drought or serious accident to the irrigation system of the United States...," making it "difficult" for the United States to deliver the required amount of water.

The Upper Colorado River Compact of 1948 allocated the Upper Basin's share of Colorado River water among the Upper Basin states by percentage as 51.75, 11.25, 23.0 and 14.0 percent to Colorado, New Mexico, Utah and Wyoming, respectively. Arizona's share of the Upper Basin's allotment of Colorado River water was set at 50,000 acre-feet annually.

The U.S. Supreme Court's 1963 decision in Arizona vs. California upheld the Lower Basin apportion that was suggested in the Boulder Canyon Act of 1928. It also excluded Arizona's tributaries

from the apportionment, awarding consumptive use of their flows exclusively to Arizona and thereby increasing Arizona's relative share of mainstem supplies. The decision also specified the division of surplus mainstem water as 46, 50, and 4 percent to Arizona, California and Nevada, respectively. The Secretary of the Interior was to determine when surplus water was available and how any curtailments would be accomplished.

The Colorado River Basin Project Act of 1968 made the Arizona mainstem diversions under the Central Arizona Project junior to the first 4.4 million acre-feet of California's mainstem allocations, and to Nevada's and Arizona's non-CAP allocations. Section 602(a) of the 1968 Act also instructed the Secretary of the Interior to develop and adopt criteria for the operation of the series of Federal reservoirs which had been constructed to manage the river's flow. The statutory guidelines provided that the operating rules for units of the Colorado River Storage Project and Glen Canyon, in particular, will as a first priority make releases necessary for compliance with the Mexican Treaty, as second priority deliver the required 75 million acre-feet per decade to the Lower Basin states and as third priority provide carry-over storage to accomplish the first two objectives. The Act also required that parity in the active storage between Lake Powell and Lake Mead be maintained. The development of the long range operating criteria for the Colorado basin was mandated by this act. The long range operating criteria define the criteria for the operation of the series of Federal reservoirs constructed to manage the river's flow.

3. SIMULATION MODEL

3.1. Overview

The CRM model was used to simulate the allocation of water in the Colorado River basin in accordance with water right priorities and the "Law of the River," subject to the constraints imposed by the hydrology and physical features of the basin. The model also simulates the salinity concentrations and hydro-electric power generation in the Colorado River basin. The model operations consist of water allocation, reservoir operations, evaporation, hydropower, and salinity. Special operations resulting from the Law of the River include flood control releases, objective release from Lake Powell and Lake Mead, the Lower Basin compact call, and the declaration and quantification of shortages and surpluses in the system. The model structure, inflow hydrology, depletions, initial conditions, and operations are described below.

3.2. Structure

Simulations of the Colorado River system is achieved using a network flow programming model. The model, like MODSIM (Shafer, 1979; Labadie et al., 1983) and its predecessor SIMYLD (Texas Water Development Board, 1972), uses the out-of-kilter algorithm (Clasen, 1968; Barr et al., 1974) to perform, at each time-step, a static optimization that simulates water allocation for a given system of priorities in a river basin network. The model is similar in structure to the model used by Brown et al. (1988, 1990) in a study of the disposition of streamflow increases from the Arapaho National Forest. The model performs three basic tasks: (1) manage input and output of data and run-control information, (2) convert a problem stated in hydrological terms into one amenable to solution by the out-of-kilter algorithm, and (3) use the algorithm to solve the network flow problem.

At each time step, the model finds the "least cost" set of flows in a network of arcs connected by nodes. Each arc has an upper and lower bound constraining the amount of water it can accommodate, and a "cost" associated with moving one unit of flow along it. An arc may represent a river segment, reservoir storage, a hydropower turbine, a consumptive use demand, or a system outflow (e.g., to the Gulf of California).

The optimization capability of the CRM is used for the efficient simulation of the operation of the Colorado River system. Where system operating policies can be represented by arc constraints and costs, they can be easily adjusted by changing the parameters corresponding to them, hence the model is very flexible in examining different institutional settings. In order to simulate the current institutional rules for water allocation, the costs of the arcs are set to represent the relative priorities that currently exist among diversions. Once a solution is found for a given time step, the reservoir contents resulting from that solution are used as the beginning contents for the next month's simulation.

Water movement and disposition in the Colorado River Basin is modeled by aggregating over time and space at the level of detail used by the U.S. Bureau of Reclamation's (USBR) Colorado River Simulation Model (CRSM) of the Basin (Schuster, 1987). Thus, a monthly time step was used; all major river reaches were included; 14 basin reservoirs were included; inflows and flow gains/losses were modeled at 29 points; 265 individual consumptive use points were recognized; and more than 107 river reaches were modeled. This detail gives the model network 211 nodes and about 580 arcs. The inflow points, reservoirs and use points are listed in Appendix A.

3.3. Inflow Hydrology

A synthetic inflow hydrology was used for this study spanning a 1400-year period. Synthetic flows were generated using SPIGOT (Grygier and Stedinger, 1988 and 1990), a stochastic streamflow generation software package developed at Cornell University. SPIGOT can be used to generate synthetic streamflows which have similar statistics to those of the historical period. The generated streamflows preserve cross-correlations between stations and serial correlation between months as well as the standard deviations and lag-1 serial correlations observed in the historic traces. The mean of the synthetic inflow set is 15 maf, which corresponds to the mean of the historical inflow hydrology from 1906 to 1983. The annual means of the flows generated by SPIGOT are within 0.5% of the historical means at Lee Ferry for their respective parent periods.

3.4. Diversions, Depletions and Return Flow

Water use estimates used in the CRM are stated in terms of "depletion", i.e., the amount of water delivered for use less the amount of water that returns to the river after use. Depletions at 265 points in the Colorado River basin are simulated in the CRM. A listing of the depletion points is given in Appendix B.

Three levels of depletions were used in this study. They correspond to the year 1991, 2010 and 2030 depletion levels. The depletion estimates have, for the most part, been derived from data developed by the USBR for its 1991 Annual Operating Plan (AOP), dated July 22, 1991 (USBR, 1991). The future depletion levels were developed by the Bureau through model studies that included consideration of water supply, legal entitlement, current and expected delivery capacity, and expected development of water-using projects.

The monthly depletions used in the CRM are derived by multiplying the annual depletion by a distribution factor for each month. Each use can have a different distribution factor. The distribution factors used are from the USBR 1991 AOP data set.

The CRM simulates depletions at diversion points except for the Dolores/San Juan export that is simulated as a diversion and return flow. Simulation of depletions represents an implicit assumption that return flows accrue above the next diversion point with no lag. This assumption is generally correct for most of the diversion points in the data set. For the diversion points where this assumption is not correct the impact will be to overstate water availability (understate environmental impacts) between the diversion point and the point at which its return flows actually accrue. Because the overall water budget is not affected, the principal result is a reduction in the precision with which the spatial distribution of shortages are represented. Most of the diversions with remote return flows are small, so that even this effect should be minimal.

3.5. Study Period and Initial Conditions

System starting conditions are set by initializing reservoir starting contents. Starting conditions for the system reservoirs are shown in Table 1.

Table 1.

Reservoir Initial Conditions

Reservoir	Active Capacity	Active Starting Contents (kaf)
Fontenelle	345	167
Flaming Gorge	3,749	3,014
Starvation	255	255
Taylor Park	106	55
Blue Mesa	830	581
Morrow Point	117	110
Crystal	18	15
Navaho	1,642	1,528
Powell	24,322	10,269
Mead	27,019	19,727
Mohave	1,810	1,623
Havasu	619	550
McPhee	381	381
Ridgway	55	55

3.6. Model Operations

The CRM simulates the physical operation of the basin and the "Law of the River." The model operations consist of water allocation to consumptive uses, storage and instream flow; reservoir operations including evaporation, sedimentation and bank storage; hydropower generation; salinity; and

the special operations. The special operations consist of flood control releases, objective minimum release from Lake Powell, inflow forecasting, calculation of 602(a) storage, equalization between Lakes Powell and Mead, and the declaration and quantification of shortages and surpluses in the Colorado basin.

3.6.1. Water Allocation

Water is allocated within the basin according to the priorities established by the interstate compacts, treaty, state laws, court decisions, and existing operating rules for storage and delivery of the water. Within these constraints, allocations to consumptive uses are made on a priority basis.

Instream Flows

In the baseline configuration of the CRM, allocations are first made to the instream flow reaches. Ten instream flow reaches are represented in the Model. These are:

Green River below Fontenelle
Green River below Flaming Gorge
Yampa River above confluence with Green River (below little Snake River)
White River above confluence with Green River
Gunnison River below Curecanti Project
San Juan River above confluence with Colorado
Colorado River above Lake Powell (below confluence with Green River)
Colorado River below Glen Canyon Dam
Colorado River below Hoover Dam
Colorado River below Parker Dam

We have assumed that, because any instream flow requirements would arise from mandates under the Endangered Species Act, allocations to these reaches will have the highest priority in the basin.

Upper Basin Consumptive Uses

The CRM allocates water to consumptive uses and storage in the system such that all institutional priorities are met, including mandated instream flows. Conceptually, the system is divided into two systems corresponding to the Upper and Lower Basins.

In the Upper Basin, water is allocated within each state according to a set of priorities. Each depletion has an assignable, relative priority; i.e., any depletion may be assigned a priority senior or junior to any other priority in the same state. The set of priorities used assigns agricultural uses the highest priority, followed by municipal uses and exports, followed by minerals, then thermal power and finally coal gas and oil shale. This ordering reflects the general order of development of water rights in the states but does not accurately reflect recent conversions of senior agricultural rights to municipal uses.

A special priority "threshold" allows the user to determine which water uses in the Upper Basin will be considered as "present perfected rights" (PPR's). In the event of a Compact call, each state's curtailment will be determined and applied in such a way that only administrable (non-PPR) uses will

be curtailed. Local shortages may occur to any depletion located on a tributary; in that event, shortfalls will occur according to the relative priorities on the tributary.

Upper Basin Storage

In the baseline configuration of the CRM, storage in the Federal reservoirs in the Upper Basin are considered junior to consumptive uses.

Lower Basin Consumptive Uses and Storage

Priorities in the Lower Basin are handled differently than those in the Upper Basin because allocations to the most junior uses in the Lower Basin are governed largely by policies such as the shortage and surplus strategies. In the CRM, the Mexico delivery obligation is given the highest priority, followed by consumptive uses other than MWD-excess and CAP. Mohave and Havasu target storage are satisfied next, followed by CAP "shortage" deliveries (see Section 3.6.6). Water stored below the shortage elevation in Lake Mead has the next priority, followed by deliveries to CAP sufficient to meet its "scheduled" delivery. The next priority is Mead storage above the "shortage" level and below the flood control pool.

Lowest priority is assigned to the MWD-excess and CAP-excess requests. Thus, only Lower Basin spills, flood control releases from Mead, and storage above the target levels of Mohave and Havasu are available to meet the last portion of the MWD-excess and CAP-excess requests. Deliveries to the excess requests are divided equally between the MWD and CAP until one or the other is fully satisfied, and then entirely to the user with remaining capacity (following Article II (B)(2) of the Supreme Court decree in *Arizona* vs. *California*).

To summarize, the water allocation priorities in the Lower Basin are as follows:

1. Mexico delivery
2. Lower Basin consumptive use except MWD-excess and CAP
3. Mohave and Havasu target storage
4. CAP "shortage" deliveries
5. Mead "shortage" storage
6. CAP "scheduled" deliveries
7. Mead storage above the "shortage" level and below the target level
8. CAP-excess and MWD-excess use
9. Storage above the target storage levels of each reservoir.

3.6.2. Reservoir operations

The 14 reservoirs simulated in the model contain a total active capacity of 61,375,000 acre-feet. One of the reservoirs, Starvation, is a composite reservoir representing an aggregation of eight actual reservoirs on the Duchesne River. Production of hydro-electric power is simulated at all reservoirs except Starvation, Taylor Park, and Ridgway. Although the McPhee and Navajo hydropower plants are still under construction, they are expected to be in operation within the next two years, and are included in the model.

The storage capacity of the reservoirs is modeled by dividing the storage capacity at a reservoir into two parts, one representing target storage, the level of storage that the USBR attempts to meet to maintain power production and provide carryover storage (Schuster, 1988), and the other representing surplus (above target) storage. For some reservoirs, target storage is constant, while for others it varies from month to month.

Releases from Powell and Mead are determined in a similar fashion to the CRSM model (Schuster, 1988). Comparison of CRM and CRSM output for a 78-year simulation over the historic period showed that the two models give very similar monthly storage levels for Powell and Mead. A general description of operations at Powell and Mead is provided here; more detail regarding operations is provided in Section 3.6.6.

Releases from Powell are set to the "objective minimum release". The amount of the objective minimum release is 8.23 maf per year as set out in the Operating Criteria (see discussion in Section 3..6.6). Releases in excess of the objective minimum release are made when spills occur or when additional releases are indicated by the rules governing equalization of storage between Powell and Mead.

The CRM treats the 8.25 maf delivery criterion as a delivery obligation and continues to call for that much water even after Lake Powell is at dead storage. Releases less than the objective minimum release will be made only when Lake Powell is at dead storage, when there is insufficient inflow to the reservoir to supply the 8.23 maf objective release and when all Upper Basin water rights junior to the Compact have ceased diverting. Rights in the Upper Basin that are not "present perfected rights", i.e. were not perfected prior to June 15, 1929 (the date of enactment of the Boulder Canyon Project Act) are subject to calls for water under the compact.

Releases from Lake Mead are based on three factors--forecasted inflows, requests for consumptive use releases, and flood control objectives. Over the entire year, at least 1.5 maf of flood control space is maintained in Mead. During the period from January to July, additional flood control releases are made, if necessary, on the basis of predicted inflow versus expected releases for consumptive use, with the goal of reaching August 1 with only 1.5 maf of flood control storage space available. During the period from August to December releases are made as necessary to end up on January 1 with 7.14 maf of flood storage space among Mead, Powell, Flaming Gorge, Blue Mesa, and Navajo Reservoirs.

3.6.3. Evaporation

Reservoir evaporation is computed at the end of each month from surface area/volume relationships and unit evaporation rates adopted from the USBR's CRSS model control file (USBR, 1991).

3.6.4. Hydropower Generation

Production of hydro-electric energy is simulated at all reservoirs except Starvation, Taylor Park, and Ridgway. Although the McPhee and Navajo hydropower plants are still under construction, they are expected to be in operation within the next two years, and are included in the model.

The simulation model does not consider hydropower outputs in determining water allocations, but computes the energy production *ex post* as a function of (1) the amount of water that passes through the turbines, (2) the feet of effective head that the water drops, and (3) power plant efficiency, generator capacity, and turbine capacity. For each hydroelectric dam, energy production for time period (i.e., month) **i** in megawatt hours (MWH) is computed as:

$$MWHi = H_i * Q_i * Ef_i * C \qquad (1)$$

subject to

$$H_i = Ep_i - Et \qquad (2)$$
$$H_i >= Hm \qquad (3)$$
$$MWH_i <= Mg \qquad (4)$$
$$Q_i <= Mt \qquad (5)$$

where:

H = head in feet at beginning of period
Q = flow in thousand acre-feet per month
Ef = generator efficiency
Hm = minimum head for intake
Mg = maximum generator capacity in MWH per month
Mt = maximum turbine capacity in thousand acre-feet per month
Ep = reservoir elevation in feet
Et = tailwater elevation in feet
C = 1.024, a constant to convert to kWH

The generator efficiency is assumed to be 0.8 for all power plants, and the tailwater elevation is assumed to be constant at each plant.

3.6.5. Salinity

Salinity concentrations, expressed in parts per million, are computed at the end of each water year in the simulation model. We assume that a complete mixing of salt occurs in the system at the end of each year. The computed salt concentration accounts for the percentage of the monthly diversions which returns to the system as return flows, and the salt concentration of the return flows. In addition, contributions from natural salt sources are accounted for in the computation of the salt concentrations.

3.6.6. Special Operations

Special operations have been implemented to simulate the requirements of the operating criteria. In general, these have been developed according to the CRSM code and the System Overview (Schuster, 1988) using data from the CRSM control file (USBR, 1991). Important operations are

described below. These include the flood control releases, objective minimum release from Lake Powell, inflow forecasting, calculation of the 602(a) storage, equalization of the storage contents of Lakes Powell and Mead, lower basin compact call, and the declaration and quantification of shortages and surpluses.

Flood control releases

Flood control operations are conducted at Lake Powell by allocating some storage space exclusively for flood control. The exclusive flood storage space is used for the temporary detention of high inflows until they can be safely discharged below the dam without causing flood flows. This is achieved through the monthly storage targets specified for Lake Powell. Five different flood control operating policies were considered in this study and are described in detail in Section 4.

Flood control operations at Lake Mead are of two types, depending on the season. From January through July, releases from Lake Mead are made at a rate such that at least a 1.5 maf of vacant space is available in Lake Mead. The release for the current month considers the anticipated releases at Lake Powell flowing into Lake Mead, plus the maximum forecasted reach inflow between Lake Powell and Lake Mead from the current month through July. Anticipated releases are also estimated based in part on available space in Powell. Flood releases from Lake Mead are then set at one of six standard flow rates--19,000 cfs, 28,000 cfs, 35,000 cfs, 40,000 cfs, or 73,000 cfs. If the flow required to maintain the 1.5 maf flood space falls between two of the standard rates, the higher level is selected.

From August through September, releases are made sufficient to meet specific, monthly space requirements in Lake Mead. These space requirements are calculated based in part on creditable space in Powell, Flaming Gorge, Blue Mesa and Navaho reservoirs. There are no restrictions (other than physical capacity) set on flood releases during this period.

Flood releases are distributed to CAP and the Metropolitan Water District of Southern California (MWD). Each entity is given half of the flood release up to its capacity. Any excess flood release is given to the entity which has leftover capacity. Flood releases in excess of the combined capacity of CAP and MWD are given to Mexico.

Objective release

The term "objective minimum release" refers to the annual release of 8.23 maf from Lake Powell to the Lower Basin according to the terms of the Operating Criteria. Although the Operating Criteria are not an interpretation of the 1922 Colorado River Compact, the 8.23 maf objective minimum release is derived from the terms of the 1922 Compact and the Mexican Treaty of 1944.

The Compact obligates the Upper Basin to deliver to the Lower Basin a sum of 75 maf over every ten-year period. Thus, a release of 7.5 maf in every year would meet the terms of the compact. The Mexican Treaty requires the U.S. to deliver 1.5 maf to Mexico each year. If half of this obligation is to be met by the Upper Basin, the total average annual release required to meet the terms of the Compact and Treaty would be 8.25 maf. The Paria River delivers an average of 20,000 acre-feet at the compact point below Lake Powell, so the average annual release can be reduced to 8.23 maf. This amount is distributed according to the monthly pattern shown in Table 2.

Table 2.

Objective Minimum Release (kaf)

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
568	560	856	889	527	510	518	551	585	1045	1012	609	8230

Releases in excess of the objective minimum release can be made to equalize Lakes Powell and Mead or to deliver surplus to the Lower Basin. Releases are held to the objective minimum release of 8.23 maf unless Powell is empty, there is insufficient inflow to meet the 8.23 maf objective and all junior rights in the Upper Basin have ceased diverting.

Inflow forecasting

Inflow forecasts are required for equalization and flood control. The CRM, like CRSM, does not make forecasts from primary information such as snowpack water content and soil moisture. Forecasts are simulated from known future inflows. Although CRSM has the capability to apply an error term, which includes a random component, to the known future inflows, this approach is not normally used. The CRM currently does not use an error term so inflow forecasts are based on perfect knowledge of future flows.

Calculation of the 602(a) storage criterion

The 602(a) storage criterion, according to section 602(a) of the Colorado River Basin Project Act (Public Law 90-537), is that quantity of storage necessary to insure that the Upper Basin can meet its future deliveries to the Lower Basin without impairing Upper Basin consumptive uses.

As it is currently implemented in the CRSM and CRM, the 602a storage level is the quantity of active storage above minimum power pool in Lake Powell which would guarantee 12 years' of Upper Basin depletions plus 12 years' of compact deliveries to the Lower Basin if the next 12 years' inflow were as low as the driest 12 years on record. The equalization level is 21 million acre feet (maf) using year 2010 depletions and 25 maf using year 2030 depletions. The live capacity of Lake Powell is about 24.5 maf.

Equalization

Equalization of storage between Lakes Powell and Lake Mead is provided for in the Operating Criteria. It calls for releases from Lake Powell into Lake Mead to equalize the September 30 contents of the two reservoirs. Equalization releases are required if: (1) the forecasted end-of-water-year (EOWY) contents in Powell are greater than the Mead forecasted EOWY contents; (2) the Upper Basin contents are greater than the 602(a) storage criterion of that date; and (3) the Mead forecasted EOWY vacant space satisfies flood control requirements.

Equalization releases from Powell are made gradually over the remaining months of the water year to bring about the equalization of Powell and Mead storage by September 30. Equalization releases only affect Lower Basin supplies to the extent that Mead elevations are kept above shortage levels.

Compact Call

The Colorado River Compact of 1922 mandated that the Upper Basin deliver to the Lower Basin a 10-year moving average of 7.5 million acre-feet at Lee Ferry . This obligation is modeled in the simulation model by computing, at the beginning of each month, the average release from Lake Powell over the previous 10 years. If the 10-year average release is below the mandated annual mean of 7.5 million acre-feet (or 10-year monthly mean of 626 kaf), then a release required to bring the average up to the 10-year Upper Basin delivery mean target at the end of the month is made from Lake Powell. As implemented in the model, this obligatory release is made even if Lake Powell is empty, in which case some Upper Basin consumptive uses are foregone in order to satisfy the required release. At the beginning of the study period, the 10-year moving average delivery is set equal to the 8.23 minimum objective release from Lake Powell.

The Lower Basin compact, as implemented, cannot call out water depletions of the present perfected rights (i.e. water rights perfected prior to June 15, 1929, the date of enactment of the Boulder Canyon Project Act) in the Upper Basin. This was done based upon the interpretation of the Colorado River Compact, Boulder Canyon Project Act, the Colorado River Basin Project Act and Arizona vs. California.

Declaration and quantification of shortage

In January, if the volume of Lake Mead is below 10.762 maf a shortage is declared and CAP is cut back to a minimum annual delivery of 450 kaf/yr (also referred to as the CAP "shortage" delivery). There are no intermediate shortage levels for CAP between the scheduled and shortage delivery level.

Thus, CAP cannot exercise its scheduled delivery against Lake Mead when the storage in that reservoir is below the shortage elevation. This subordination of low priority CAP requests reflects one interpretation of the 1963 Supreme Court decision in Arizona vs. California and the Colorado River Basin Project Act (Schuster, 1988, p. 73). The shortage elevation and shortage delivery defined by the USBR and used in this study have been set empirically so that subsequent operations will be unlikely to draw Lake Mead below the minimum power pool (1083 feet). This not only protects hydropower production, but also reduces the chance of future shortfalls to future consumptive uses of higher priority (e.g., California and other mainstem uses). The experiments that led to the adoption of the currently-adopted shortage elevation were undertaken using the historic period as a basis, thus the shortage elevation may not be appropriate for different hydrological conditions.

Shortages equal to 4% of the CAP shortage are also imposed on Nevada. No other shortages are imposed on the Lower Basin unless: (1) there are local shortages (these are sometimes observed on the Virgin River); or (2) Lake Mead empties. If Lake Mead empties, shortages fall first on CAP and then on MWD. If Lake Mead empties, shortages are imposed on Mexico in proportion to the total, predicted U.S. shortage.

Declaration and quantification of surplus

The surplus strategy is intended release of surplus water in scheduled amounts to increase the benefits of water use above those that would be realized with unscheduled flood control releases. A surplus is declared in October if the combined contents in Lakes Powell and Mead plus a 70% probability inflow exceed a specified Powell/Mead target. The Powell/Mead target considers the capacities of the two reservoirs and the flood control space required in September.

If a surplus is predicted, it is distributed evenly between CAP and MWD up to their capacities. If 200 kaf remain after MWD and CAP receive their allocations, Mexico is given an additional 200 kaf.

Surplus allocations are met by releases from Lake Mead. Surplus releases from Lake Powell are made if the current contents of Lake Powell plus the average inflow exceeds a target. The Powell target considers the equalization level and current contents in Flaming Gorge, Blue Mesa and Navaho reservoirs. Higher contents in those reservoirs result in a lower Powell target, which results in higher surplus releases.

4. GLEN CANYON DAM FLOOD CONTROL OPERATIONS

Releases from Glen Canyon Dam are driven by operational objectives in the Colorado River System and the Operating Criteria described in the previous section. Those that influence releases from Glen Canyon Dam include objective minimum release, storage equalization between Lakes Powell and Mead, and flood operations.

The CRM makes releases through the river outlets and/or spillways at Glen Canyon Dam only when such releases are in excess of the powerplant capacity of 33,200 cfs. Such releases are termed "excessive" and are avoided as a matter of policy because they reduce energy output and can lead to environmental impacts below the dam.

Because the focus of this study was on flood control operations at Glen Canyon Dam, operations that do not involve flood control at Glen Canyon Dam were simulated without modification, but changes were made to the flood control operations to simulate five different schemes. The first scheme assumes no flood control measure is in place. The next three schemes, including the current operating scheme at Glen Canyon Dam, simulate flood control operations by maintaining exclusive flood spaces in Lake Powell following specific schedules. The fifth operational scheme considered is related to the proposed structural measure to increase Lake Powell's total capacity, with the increased capacity used as a flood pool (Operation of Glen Canyon Dam Draft EIS, 1993). The flood storage space created in the operational or structural schemes is used for the temporary detention of high inflows that may cause excessive or flood flows below the dam, until such inflows can be discharged without exceeding the powerplant capacity of the dam. The five operational schemes are described below.

4.1. No-Flood Control Operation

Under this scheme, no space is provided in Lake Powell for exclusive flood control use. The lake is allowed to fill whenever there are enough inflows to do so, i.e., the storage targets are set to the maximum reservoir storage content in each month of the year.

4.2. Maintain Operating Policies As They Are Now

The current operating policies were gleaned from the USDOI, 1993, report, and confirmed through discussions with Bureau of Reclamation personnel (Vickers, 1994). The policies call for an active storage target of 22.6 maf for Lake Powell by January 1 of each year. Since the capacity of Lake Powell is 24.322 maf, the flood space is then 1.722 maf by January 1. The current operating policies also prescribe a target for July 1 as if Lake Powell has 0.5 maf less capacity than it actually

has, i.e., an active storage target of 23.822 maf or a flood space of 0.5 maf. Between January 1 and July 1, Lake Powell is operated using inflow forecasts, with a protection factor added to the forecasted inflow that corresponds to the maximum forecast error ever experienced for that month. The goal of the forecasts is to meet the active storage targets between January 1 and July 1, depicted in this study as a straight line interpolation of the January 1 (22.6 maf) and July 1 (23.822 maf) targets. After July 1, the forecasts are quite accurate, and Lake Powell is allowed to fill if there are enough inflows. The reservoir is then gradually brought down starting from October 1 so as to meet the January 1 target of 22.6 maf after reaching its highest point.

The current operating policies, as described above, were simulated with the CRM through the use of end-of-month active storage targets for Lake Powell. The CRM tries to meet these targets within the existing physical and institutional constraints described in Sections 2 and 3. The resulting end-of-month target, flood space and total capacity are shown in Figure 2 and Table 3. Note that the end-of-month targets shown in the figure and table correspond to the beginning-of-month targets for the following month. For example, the end-of-month target for June is the same as the target for July 1.

Table 3.

End-of-Month Storage Target, Flood Space and Total Capacity for No Action or Current Operating Policy (units in kaf)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Target	23748	23174	22600	22804	23007	23211	23415	23618	23822	24322	24322	24322
Flood Space	574	1148	1722	1518	1315	1111	907	704	500	0	0	0
Total Cap	24322	24322	24322	24322	24322	24322	24322	24322	24322	24322	24322	24322

4.3. Operational Scheme To Provide *Additional* Flood Space of 0.5 maf in Lake Powell

Under this scheme, an additional, exclusive flood space of 0.5 maf is provided--beyond the flood protection space prescribed in the current operating policies--during the flood season from January 1 through July 1. Hence, the active storage target for Lake Powell is 22.1 maf by January 1 of each year. Since the capacity of Lake Powell is 24.322 maf, the flood space is then 2.222 maf. The target for July 1 is set as if Lake Powell has 1 maf (0.5 maf under the current policy plus the additional 0.5 maf) less capacity than it actually has, i.e., it has a flood space of 1 maf or an active storage target of 23.322 maf.

The above scheme is implemented in the model by lowering the active storage targets under the current operating policies by 0.5 maf from January 1 through July 1. The resulting end-of-month storage target, flood space, and total capacity for Lake Powell are shown in Figure 2 and Table 4.

Figure 2

End-Of-Month Active Storage Targets At Lake Powell For Non-Structural Flood Avoidance Policies

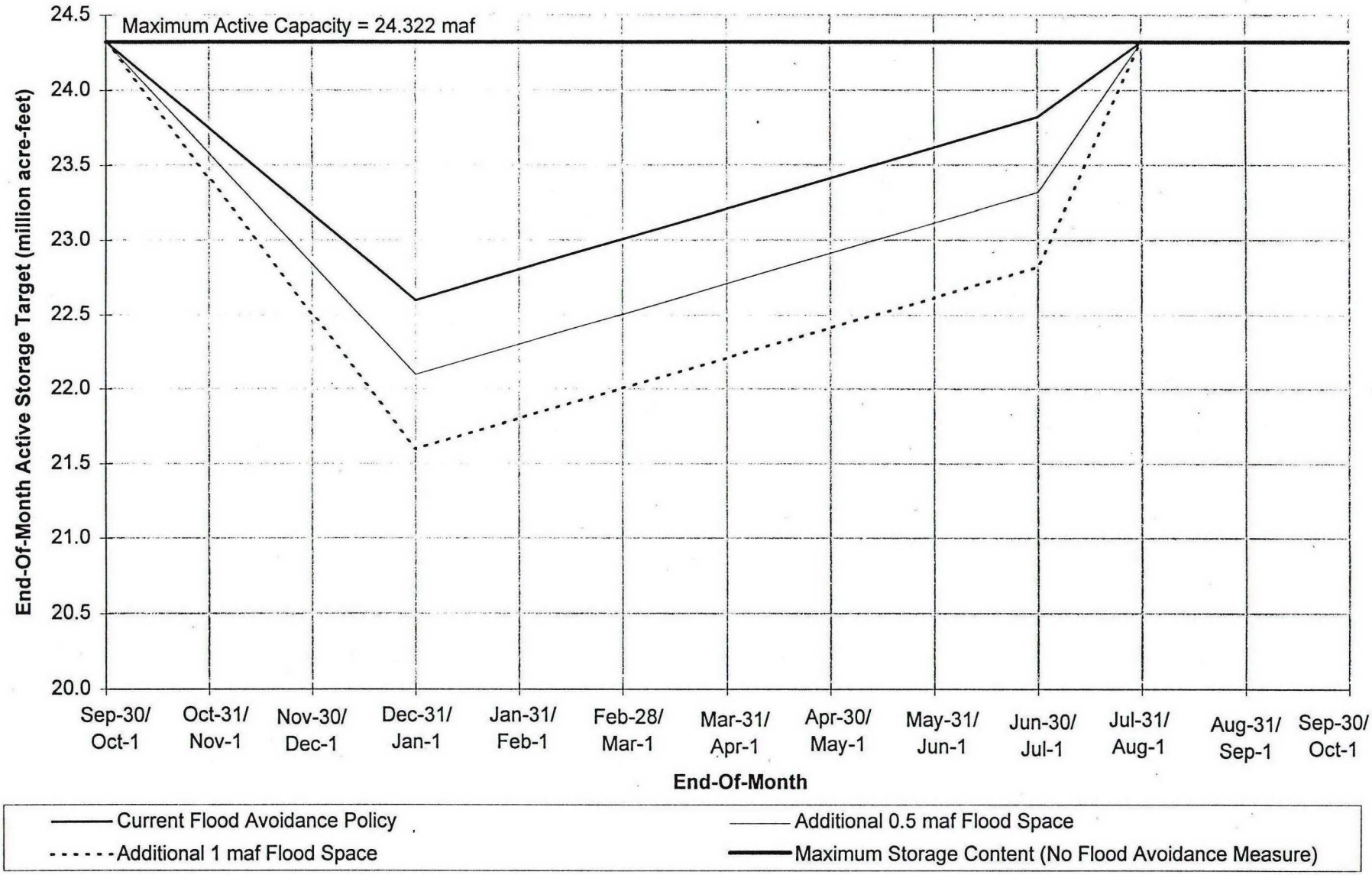


Table 4.

End-of-Month Storage Target, Flood Space and Total Capacity for Operational Scheme to Provide Additional Flood Space of 0.5 maf Beyond the Existing Flood Control Space (units in kaf)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Target	23581	22841	22100	22304	22507	22711	22915	22118	23322	24322	24322	24322
Flood Space	741	1481	2222	2018	1815	1611	1407	2204	1000	0	0	0
Total Cap	24322	24322	24322	24322	24322	24322	24322	24322	24322	24322	24322	24322

4.4. Operational Scheme To Provide An *Additional* Flood Space of 1 maf in Lake Powell

An additional, exclusive flood space of 1 maf is provided--beyond the flood protection space prescribed in the current operating policies--during the flood season from January 1 through July 1. Hence, the active storage target for Lake Powell is set to 21.6 maf by January 1 of each year. Since the capacity of Lake Powell is 24.322 maf, the flood space is then 2.722 maf. The target for July 1 is also set as if Lake Powell has 1.5 maf (0.5 maf under the current policy plus the additional 1 maf) less capacity than it actually has, i.e., it has a flood space of 1.5 maf or an active storage target of 22.822.

The above scheme is implemented in the model by lowering the active storage targets under the current flood control policies by 1 maf from January 1 through July 1. The resulting end-of-month active storage target, flood space and total capacity for Lake Powell are shown in Figure 2 and in Table 5.

Table 5.

End-of-Month Storage Target, Flood Space and Total Capacity for Operational Scheme to Provide Additional Flood Space of 1.0 maf Beyond the Existing Flood Control Space (units in kaf)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Target	23415	22507	21600	21804	22007	22211	22415	22618	22822	24322	24322	24322
Flood Space	907	1815	2722	2518	2315	2111	1907	1704	1500	0	0	0
Total Cap	24322	24322	24322	24322	24322	24322	24322	24322	24322	24322	24322	24322

4.5. Structural Measure To Increase Lake Powell's Flood Pool By 0.75 maf

Under this operational scheme, Lake Powell's active capacity would be increased by 0.75 maf through a structural measure designed to raise the height of the four spillway gates by 4.5 feet to elevation 3704.5 feet (USDOI, 1993). The additional capacity would be used as an exclusive flood control space, and utilized only in years when the flood space under the current operating policies is insufficient.

As in the current operating policies, an active storage target of 22.6 maf is set for Lake Powell by January 1 of each year. Since the capacity of Lake Powell is now expanded to 25.072 maf (24.322 maf existing capacity plus 0.75 additional storage from the structural measure), the flood space is then 2.472 maf. The target for July 1 is set such that Lake Powell has 1.25 maf (0.5 maf under the current policy plus the additional 0.75 maf from the structural measure) less capacity than it actually has, i.e., Lake Powell has a flood space of 1.25 maf or an active storage target of 23.822. The active storage targets under this operating policy are still the same as under the current operating policy, but the flood space is now bigger by 0.75 maf throughout the year. The resulting end-of-month active storage target, flood space and total capacity for Lake Powell are shown in Figure 3 and in Table 6.

Table 6.

End-of-Month Storage Target, Flood Space and Total Capacity for Lake Powell for Structural Measure to Increase Lake Powell's Flood Pool by 0.75 maf (units in kaf)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Target	23748	23174	22600	22804	23007	23211	23415	23618	23822	24322	24322	24322
Flood Space	1324	1898	2472	2268	2065	1861	1657	1454	1250	750	750	750
Total Cap	25072	25072	25072	25072	25072	25072	25072	25072	25072	25072	25072	25072

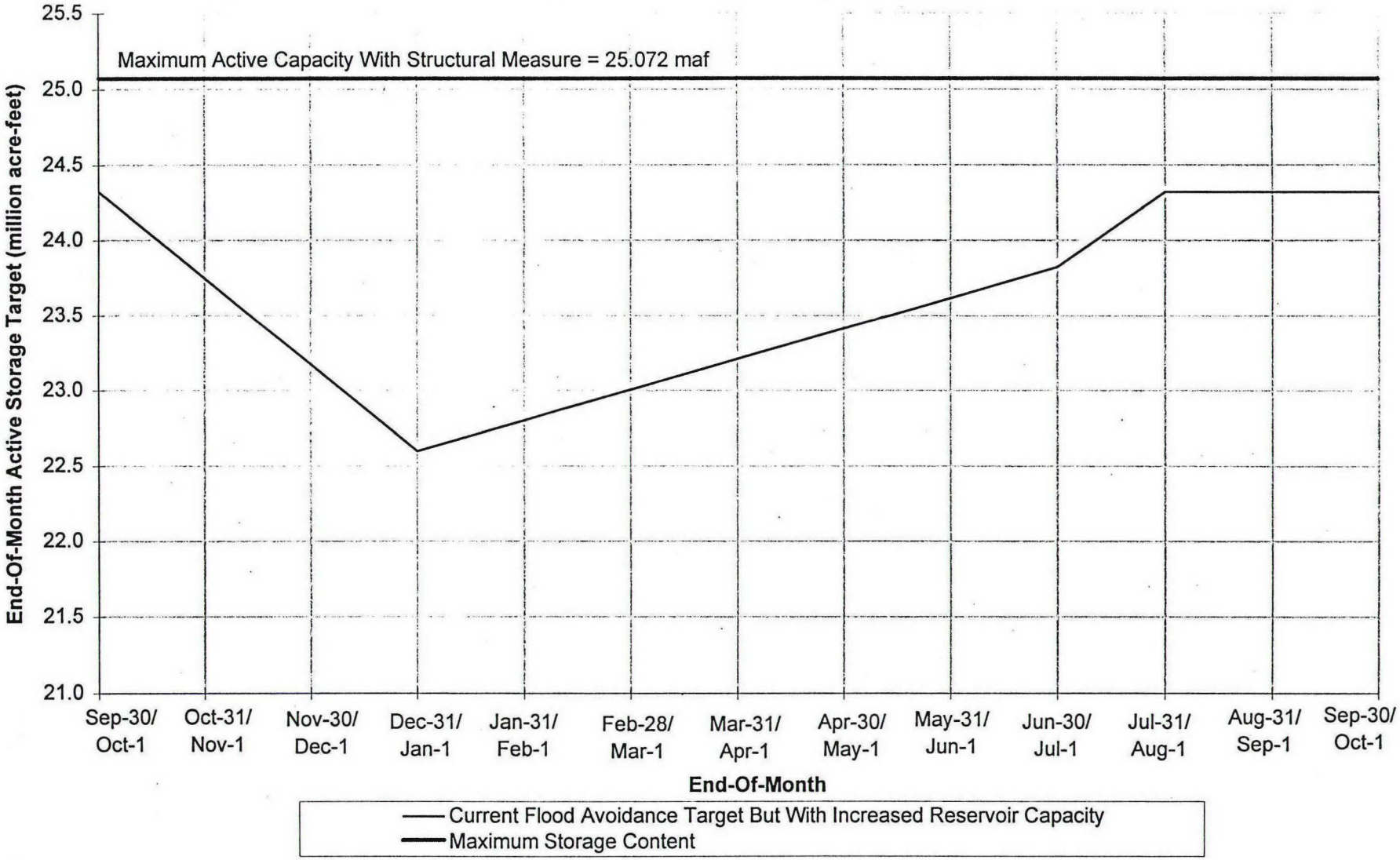
5. ANALYSES

Model simulations with the five operational schemes at Glen Canyon Dam, three depletion levels, and the synthetic streamflow trace were carried out. This combination gave a total of 15 (5x3x1) model runs. The depletion levels for years 1991, 2010 and 2030, as described in Section 3.4, were employed in the study. The virgin synthetic streamflow trace, with a mean of 15.0 maf and extending over a 1,400-year period, was used in all 15 model runs. A description of the synthetic trace was provided in Section 3.

The main variable of interest from the analysis was annual, maximum monthly flow below Glen Canyon Dam. Other variables examined were annual, maximum monthly flows below one of the Upper Basin Reservoirs (Flaming Gorge was selected for this) and below Lake Mead, water availability for beneficial use in the Colorado River basin, hydropower production at Glen Canyon Dam, and salinity below Lake Mead. The frequencies and magnitudes of these variables were examined by expressing the results as cumulative probability plots, i.e., as the percent of time the variable does not exceed a value. Results from the analyses are presented in the next section.

Figure 3

Flood Avoidance Policy Using Structural Measure To Increase The Capacity Of Lake Powell By 0.75 maf. The Additional Space Is Used All Year As A Nonviolable Flood Space



6. RESULTS AND DISCUSSION

Results from the analyses are discussed in the following three sub-sections. Each sub-section discusses the results using one of the three depletion levels for each of the five different operational schemes.

6.1. Results with Year-1991 Depletion Level

Graphs showing the results from the five operational schemes, with depletions at year-1991 levels, are given in Appendix C. The graphs show frequency distribution curves for flows below Glen Canyon Dam, Lake Mead and Flaming Gorge Reservoir, Upper and Lower Basin depletions, energy generation at Glen Canyon Dam, salinity below Lake Mead, storage contents at Lake Powell, and surface area at Lake Powell.

6.1.1. Flows Below Glen Canyon Dam

Figure C.1 shows the frequency distribution curves of annual, maximum monthly flows below Glen Canyon, for the five operational schemes over the 1400-year study period. The distribution curves were obtained by ranking the maximum, mean monthly flow in each year of the 1400-year study period (this gave a total of 1,400 flow values), and then plotting the ranked values on a percentage scale from 0 to 100. The curves show the percent of time that a particular annual, maximum monthly flow value is not exceeded.

Figure C.1 shows that over about 32 percent of the time (from the zero to about 32 percent non-exceedance range), an annual maximum monthly flow of 17,313 cfs is not exceeded under the five different operational schemes. The frequency curves for the five operational schemes are the same below the 32.2 percent non-exceedance level at which point they start to diverge. The 17,313 cfs (or 1,045 kaf) value is the maximum, monthly flow specified in the distribution pattern of the "objective minimum release" given in Table 2.

Figure C.1 also shows the Glen Canyon Dam powerplant capacity of 33,200 cfs. Flows above the 33,200 cfs level are regarded as excessive releases or flood flows. The model restrains monthly releases below this level by temporarily storing excessive inflows in the flood pool, until they can be discharged at or below the powerplant capacity. The 33,200 cfs threshold is exceeded only when Lake Powell reaches its maximum capacity, and subsequent inflows into the lake are more than the powerplant capacity. Because storage in the flood pool occurs much of the time during the runoff period, the frequency distribution exhibit a plateau at the 33,200 cfs threshold level.

It can also be observed from Figure C.1 that over the middle range of flows (from about the 32 to 75 percent non-exceedance levels), operational schemes with larger flood storage spaces (or lower storage targets) induce higher, maximum monthly flows below Glen Canyon Dam. This occurs because the operational schemes with larger flood control spaces make more releases to maintain the larger flood control space. Hence, the operational scheme with the largest flood control space (the one with an additional 1 maf flood space), generally produces the highest maximum monthly discharge in this middle flow range. This is followed by the operational scheme with an additional 0.5 maf flood space, the operational scheme with a structural measure to create an additional 0.75 maf flood space, the current operating policy, and the no-flood control policy. Although, the operational scheme with a structural measure has a larger flood control space than the operational scheme with an additional 0.5

maf flood space (see Figures 2 and 3, and Tables 5 and 6), the latter has higher, maximum monthly discharges. This happens because the operational scheme with an additional 0.5 maf flood has lower storage targets as indicated in Figure 2.

The frequency curves of operational schemes with larger flood control spaces (or lower storage targets) also stay at the 32,000 cfs threshold level for longer periods. This occurs because the larger flood space can be used to store more excessive inflows before the reservoir fills and subsequently starts to discharge at a rate above the powerplant capacity.

A magnified view of the tail section of Figure C.1 is shown as Figure C.2. The percentage of time that the annual maximum monthly flow does not exceed Glen Canyon Dam powerplant capacity can clearly be seen in this figure for the five operational schemes. These percentages are given in Table 7. Since a monthly flow above the powerplant capacity of 33,200 cfs is termed an excessive or flood flow, Table 7 also indicates the probabilities of occurrence of excessive or flood flows below Glen Canyon Dam.

Table 7.

Percent of Years that the Annual, Maximum Monthly Flows Below Glen Canyon Dam over the 1400-year Study Period do not Exceed (or Exceed) Glen Canyon Dam's Powerplant Capacity of 33,200 cfs, for the Five Operational Schemes with Year-1991 Depletions

Operational Scheme	Percent Of Time Not Exceeded	Percent of Time Exceeded
No Flood Control Operation	88.9%	11.1%
Maintain Operating Policies As They Are Now	93.2%	6.8%
Operational Scheme To Provide An Additional Flood Space of 0.5 maf	94.4%	5.6%
Operational Scheme To Provide An Additional Flood Space of 1 maf	96.2%	3.8%
Structural Scheme To Increase Flood Pool by 0.75 maf	95.7%	4.3%

Flows towards the extreme tail section of the frequency distribution curves, for example, at the 98th or 99th percent non-exceedance levels, are very high for all the operational schemes, indicating that none of the flood control policies is completely effective in reducing maximum monthly flows below Glen Canyon Dam in the extreme inflow years.

6.1.2. Flows Below Lake Mead and Flaming Gorge Reservoir

Figures C.3 shows the frequency distribution curves of annual, maximum monthly flows below Lake Mead (Hoover Dam), for the five operational schemes over the 1400-year study period. The annual, maximum monthly flows are the same in the five operational schemes up to about the 50 percent non-exceedance level, before they start to diverge. The plateau at a discharge level of 28,000 cfs observed in the graph, corresponds to one of the five flood control discharge rates for Lake Mead. The flood control discharge rates for Lake Mead are the forecast release levels that, if kept constant

from January through July, would keep a flood control space of at least 1.5 maf in Lake Mead. The 35,000 cfs flood release level also shows up in the figure. The annual, maximum monthly flows in the operating scheme with the structural measure are lower than the others because of the increased total capacity in Lake Powell, which is one of the factors considered to determine the flood release rate from Lake Mead.

Figure C.4 shows the frequency distribution curves of annual, maximum monthly flows below Flaming Gorge Dam, for the five operational schemes over the 1400-year study period. The capacity of the combined river and power outlet works at Flaming Gorge Dam of 7,277 cfs shows up in the figure as the flat portion of the distribution curves from about the 88 to 97/98 percent non-exceedance range. Releases from the dam are maintained at this level until the reservoir fills up, and subsequent inflows exceed the combined river and power outlet capacities. Inflows above the combined outlet works are then released through the spillway. This occurs starting from the 96.7 percent non-exceedance level for the no-flood control scenario, from the 97.7 percent non-exceedance level for the current flood control scenario, from the 98.0 not-exceedance level for the structural measure scenario, from the 98.1 for the 0.5 maf additional flood space scenario, and from the 98.7 non-exceedance level for the 1 maf additional flood space scenario.

6.1.3. Lower and Upper Basin Depletions

6.1.3.1. Lower Basin Depletions

Figure C-5 shows the frequency distribution curves of total annual depletions in the Lower Basin, for the five operational schemes over the 1400-year study period. A low and high depletion level, as well as a transition region between the low and high levels can be observed from this figure. The low depletion level, at 7.141 maf, is the total annual depletion at year-1991 levels in the Lower Basin under normal circumstances, i.e., when no shortages or surpluses were declared. The depletions are at this level about 32 percent of the time (from the 0 to about the 32 percent non-exceedance range) under the five operational schemes. The high depletion level, at 7.705 maf, is the total annual depletion in the Lower Basin under surplus conditions, when MWD was diverting water at the full capacity of its canal.

The various depletions in the transitional region between the low and high depletion levels, shown in Figure C-5, are entirely due to surplus water taken by MWD. The transitional region indicate those years when MWD was able to take surplus water, but the available surplus water was not enough for MWD to use the full capacity of its canal. The other entity that could take surplus water, CAP, did not take it when surplus conditions were declared, because the 1991 depletion levels used herein assumed that there was no demand for CAP surplus water; only MWD took surplus water because there was a demand for it. The figure also shows that, under the five operational schemes, MWD was able to take surplus water up to the full capacity of its canal in about 55 percent (from about the 45 to the 99.9 percent non-exceedance range) of the years.

From Figure C-5, we can conclude that the different flood control operational schemes at Glen Canyon Dam do not affect Lower Basin depletions under normal, and full surplus conditions. The operational schemes, however, affect total annual depletions in the Lower Basin (specifically, MWD) in the transitional range when a surplus condition is declared, but the additional water from the surplus is not enough for MWD to take it up to its full canal capacity. In such instances, MWD is able to take more surplus water under operational schemes with less flood control spaces (or higher storage targets), than under operational schemes with more flood control spaces (or lower storage targets). This

observation can be made from Figure C-5. This happens because the lower storage targets aimed for Lake Powell evacuate more water from Powell which in some cases cannot be captured by Lake Mead because Lake Mead is in flood control operation.

6.1.3.1. Upper Basin Depletions

Figure C-6 shows the frequency distribution curves of total, annual depletions in the Upper Basin, for the five operational schemes over the 1400-year study period. The figure shows that the different flood control operational schemes employed at Glen Canyon Dam do not have any effect on the total, annual depletions in the Upper Basin.

6.1.4. Energy Generation at Glen Canyon Dam

Figure C-7 shows that the total annual energy generated at Glen Canyon Dam is about the same under the five operational schemes. In about 20 percent of the 1400-year period (between the zero and about 20 percent not-exceedance range), the generated energy are almost equal under the five operational schemes. In about 30 percent of the time (between about the 20 and 50 percent non-exceedance range), slightly more energy is generated under operational schemes with smaller flood control spaces because Lake Powell is kept slightly higher. In about 50 percent of the time (between about the 50 to the 99.9 percent not-exceedance range), more energy is generated under the operational schemes with bigger flood control spaces because more releases are made from Lake Powell. Table 8 gives the annual energy generated at different exceedance levels at Glen Canyon Dam for the five operational schemes over the 1400-year study period.

Table 8

Total Annual Energy Generated at Different Non-Exceedance Levels at Glen Canyon Dam over the 1400-Year Study Period, for the Five Operation Schemes with Depletions at Year-1991 levels (units in Giga Watt Hours)

Operational Scheme	10%	25%	50%	75%	90%	1400-Yr Mean
No Flood Control Operation	4,403	4,674	5,323	6,286	7,630	5,662
Maintain Operating Policies As They Are Now	4,387	4,581	5,388	6,311	7,575	5,663
Operational Scheme To Provide An Additional Flood Space of 0.5 maf	4,371	4,523	5,401	6,354	7,487	5,644
Operational Scheme To Provide An Additional Flood Space of 1 maf	4,348	4,484	5,354	6,407	7,502	5,624
Structural Scheme To Increase Flood Pool by 0.75 maf	4,397	4,558	5,406	6,319	7,632	5,662

Overall, the most energy was generated under the operational scheme with the structural measure, because of the increased storage capacity, which reduces spills while allowing higher reservoir levels that results in higher hydraulic heads for generating power.

6.1.5. Salt Concentration Below Lake Mead

Figure C-8 shows the frequency distribution curves of annual salt concentration below Lake Mead for the five operational schemes over the 1400-year study period. It can be observed from the figure that the salt concentration below Lake Mead is not influenced by the different flood control operational schemes at Glen Canyon Dam.

6.1.6. Storage Contents and Surface Area of Lake Powell

Figures C-9 and C-10 show frequency distribution curves of storage contents and surface areas of Lake Powell, for the five operational schemes over the 1400-year study period. As expected, the storage contents and surface areas are lower under operational schemes with less flood control spaces (or higher storage targets), than under operational schemes with more flood control spaces (or lower storage targets). Hence, storage contents and surface areas under the no-flood control operational scheme were the highest, while they were the lowest under the operational scheme with an additional 1 maf flood space.

6.2. Results with Year-2010 Depletion Level

Graphs showing the results from the five flood control operational schemes at Glen Canyon Dam, with depletions at year-2010 levels, are contained in Appendix D. The graphs show frequency distribution curves for flows below Glen Canyon Dam, Lake Mead and Flaming Gorge Reservoir, Upper and Lower Basin depletions, energy generation at Glen Canyon Dam, salinity below Lake Mead, storage contents at Lake Powell, and surface area at Lake Powell.

6.2.1. Flows Below Glen Canyon Dam

Figure D-1 shows the frequency distribution curves of annual, maximum monthly flows below Glen Canyon Dam, for the five operational schemes over the 1400-year study period. The shape of, and relative differences between the frequency distribution curves are similar to those from scenarios with depletions at year-1991 levels depicted in Figure C-1. In this case, however, the frequency distribution curves are shifted a little bit to the right because the depletions at year-2010 are higher. The higher depletions result in less inflows into Lake Powell, thereby reducing outflows from Glen Canyon Dam, and decreasing the likelihood of floods or excessive releases. Because of the decreased outflows from Glen Canyon Dam, the percentage of time that releases from Glen Canyon Dam exceeds the powerplant capacity is lower, as indicated in Figure D-1.

Figure D-2 shows a magnified view of the tail section of Figure D-1; the frequency distribution curves for the five operational schemes can be more clearly seen in this figure. Flows towards the extreme tail section of the frequency distribution curves are very high for all the operational schemes, indicating that none of the flood control policies is completely effective in reducing maximum monthly flows below Glen Canyon Dam in the extreme inflow years.

Table 9 shows the percentage of time that the annual, maximum monthly flows do not exceed the 33,200 cfs threshold level. The table also indicates the probability of a flood or excessive flow occurring below Glen Canyon Dam. The table shows that the probability of occurrence is reduced, when compared to scenarios with depletions at year-1991 levels.

Table 9

Percent of Years that the Annual, Maximum Monthly Flows Below Glen Canyon Dam, over the 1400-year Study Period, do not Exceed (or Exceed) Glen Canyon Dam's Powerplant Capacity of 33,200 cfs, for the Five Operational Schemes with Year-2010 Depletions

Operational Scheme	Percent Of Time Not Exceeded	Percent of Time Exceeded
No Flood Control Operation	93.6	6.4
Maintain Operating Policies As They Are Now	96.4	3.6
Operational Scheme To Provide An Additional Flood Space of 0.5 maf	97.3	2.7
Operational Scheme To Provide An Additional Flood Space of 1 maf	98.1	1.9
Structural Scheme To Increase Flood Pool by 0.75 maf	98.1	1.9

6.2.2. Flows Below Lake Mead and Flaming Gorge Reservoir

Figure D-3 shows the frequency distribution curves of annual, maximum monthly flows below Lake Mead (Hoover Dam) for the five operational schemes over the 1400-year study period. The maximum, monthly flows are the same in the five operational schemes up to about the 82 percent non-exceedance level before they start to diverge, indicating that flows below Lake Mead would be the same 82 percent of the time. The 28,000 cfs release rate in the figure, observed over long percentage times, corresponds to one of the flood control discharge rates from Lake Mead. The flood control discharge rates are the forecast release levels that, if kept constant from January through July, would keep a flood control space of 1.5 maf in Lake Mead.

Figure D-4 shows the frequency distribution curves of annual, maximum monthly flows below Flaming Gorge Dam for the five operational schemes over the 1400-year study period. The capacity of the combined river and power outlet works at Flaming Gorge Dam of 7,277 cfs shows up as the flat portion of the distribution curves from about the 88 percent to the 98 percent non-exceedance range. Releases from the dam are maintained at this level until the reservoir fills up, and subsequent inflows exceed the combined river and power outlet capacities. Inflows above the combined outlet works are then released through the spillway. Releases through the spillway occur from the 97.9 percent non-exceedance level for the no-flood control scenario, from the 98.6 percent non-exceedance level for the current flood control scenario, from the 98.6 not-exceedance level for the structural measure scenario, from the 98.9 for the 0.5 maf additional flood space scenario, and from the 99.3 non-exceedance level for the 1 maf additional flood space scenario.

6.2.3. Upper and Lower Basin Depletions

6.2.3.1. Lower Basin Depletions

Figure D-5 shows the frequency distribution curves of total, annual depletions in the Lower Basin, for the five operational schemes over the 1400-year study. Several depletion levels can be observed from this figure, caused by shortage, normal, or surplus conditions. The lower end of the frequency distribution curves, from the zero to about the 3 percent non-exceedance range, corresponds to years when shortage conditions were declared in the Lower Basin. In these years, CAP deliveries were cut back according to the rules governing a shortage declaration. Three depletion levels fall within this range (6.841 maf, 7.194 maf, and 7.404 maf). Lower Basin depletions under normal conditions (7.758 maf), occur from about the 4 to 76 percent non-exceedance range, or about 71 percent of the time. Depletions under full surplus conditions (8.415 maf), occur from about the 84 to 99.9 percent non-exceedance range, about 16 percent of the time. A transitional region, between depletions at normal conditions and depletions at full surplus conditions, occurs from about the 77 percent to 83 percent range, or about 6 percent of the time. In this transitional range, surplus deliveries are taken by both MWD and CAP, but the surplus water is not enough to satisfy their full capacities.

It can be observed from Figure D-5 that the different flood control operational schemes at Glen Canyon Dam do not affect Lower Basin depletions under normal, shortage or full surplus conditions. The operational schemes affect Lower Basin depletions only in the transitional region between normal, and full surplus conditions. In such instances, depletions under operational schemes with less storage spaces for flood control (or operational schemes with higher storage targets) are higher than depletions under operational schemes with more storage space for flood control (or operational scheme with lower storage targets). This happens because the higher storage target aimed for at Lake Powell makes more surplus water to be available whenever a surplus condition is declared.

6.2.3.2. Upper Basin Depletions

Figure D-6 shows the frequency distribution curves of total, annual depletions in the Upper Basin, for the five operational schemes over the 1400-year study period. The figure shows that the different flood control operational schemes employed at Glen Canyon Dam do not have any effect on total, annual depletions in the Upper Basin.

6.2.4. Energy Generation at Glen Canyon Dam

Figure D-7 shows that the total, annual energy generated at Glen Canyon Dam, is about the same under the five operational schemes. In about 35 percent of the years in the 1400-year period (between the zero to about the 35 percent not-exceedance range), about the same amount of energy was generated under the five operational schemes. In about 35 percent of the time (between about the 35 to 65 percent not-exceedance range), slightly more energy is generated under operational schemes with smaller flood control spaces, because Lake Powell is kept slightly higher. In about 30 percent of the time (between about the 70 to 99.9 percent not-exceedance range), more energy is generated under the operational schemes with bigger flood control spaces, because more releases are made from Lake Powell. Table 10 gives the annual energy generated at different exceedance levels at Glen Canyon Dam for the five operational schemes over the 1400-year study period.

Table 10

Total Annual Energy Generated at Different Non-Exceedance Levels at Glen Canyon Dam over the 1400-Year Study Period, for the Five Operation Schemes, with Depletions at Year-2010 levels (units in Giga Watt Hours)

Operational Scheme	10%	25%	50%	75%	90%	1400-Yr Mean
No Flood Control Operation	4,138	4,345	4,838	5,570	6,568	5,095
Maintain Operating Policies As They Are Now	4,136	4,341	4,782	5,618	6,622	5,095
Operational Scheme To Provide An Additional Flood Space of 0.5 maf	4,125	4,333	4,722	5,642	6,623	5,085
Operational Scheme To Provide An Additional Flood Space of 1 maf	4,112	4,318	4,619	5,666	6,674	5,072
Structural Scheme To Increase Flood Pool by 0.75 maf	4,145	4,354	4,739	5,597	6,647	5,102

Overall, the most energy was generated under the operational scheme with the structural measure, because of the increased storage capacity, which reduces spills while allowing higher reservoir levels that results in higher hydraulic heads for generating power.

6.2.5. Salt Concentration Below Lake Mead

Figure D-8 shows the frequency distribution curves of annual salt concentration below Lake Mead, for the five operational schemes over the 1400-year study period. The figure shows that the flood control operational schemes have no apparent effect on salt concentration below Lake Mead.

6.2.6. Storage Contents and Surface Area of Lake Powell

Figures D-9 and D-10 show frequency distribution curves of storage contents and surface areas of Lake Powell, for the five operational schemes over the 1400-year study period. As for scenarios with depletions at year-1991 levels, the storage contents and surface areas are generally lower under operational schemes with less storage space used for flood control (or operational scheme with higher storage targets), than under operational schemes with more storage space used for flood control (or operational scheme with lower storage targets). Overall, the storage contents and surface areas were highest under the operational scheme with the structural measure, in about 70 percent of the years in the 1400-year study period.

6.3. Results with Year-2030 Depletion Level

Graphs showing the results from the five flood control operational schemes at Glen Canyon Dam, with depletions at year-2030 levels, are contained in Appendix E. The graphs show frequency distribution curves for flows below Glen Canyon Dam, Lake Mead and Flaming Gorge Reservoir, Upper and Lower Basin depletions, energy generation at Glen Canyon Dam, salinity below Lake Mead, storage contents at Lake Powell, and surface area at Lake Powell.

6.3.1. Flows Below Glen Canyon Dam

Figure E-1 shows the frequency distribution curves of annual, maximum monthly flows below Glen Canyon Dam, for the five operational schemes over the 1400-year study period. The shape of, and relative differences between the frequency distribution curves are similar to those from scenarios with depletions at year-1991 and year-2010 levels; however, they are shifted more towards the right because of the higher depletion levels in year-2030.

A magnified view of the tail section of Figure E-1 is given in Figure E-2, which shows the frequency distribution curves for the five operational schemes in greater detail. Flows towards the extreme tail section of the frequency distribution curves are very high for all the operational schemes, indicating that none of the flood control policies is completely effective in reducing maximum monthly flows below Glen Canyon Dam in the extreme inflow years.

Table 11 shows the percentage of time that the annual, maximum monthly flows over the 1400-year study period, do not exceed the 33,200 cfs threshold level. The table also indicates the probability of a flood or excessive flow occurring below Glen Canyon Dam. The table shows that the probability of occurrence of a flood or excessive flow is further reduced, compared to when depletions were at 1991 or 2010 levels.

Table 11

Percent of Years that the Annual, Maximum Monthly Flows Below Glen Canyon Dam, over the 1400-year Study Period, do not Exceed (or Exceed) Glen Canyon Dam's Powerplant Capacity of 33,200 cfs, for the Five Operational Schemes with Year-2030 Depletions

Operational Scheme	Percent Of Time Not Exceeded	Percent of Time Exceeded
No Flood Control Operation	94.2%	5.8%
Maintain Operating Policies As They Are Now	96.7%	3.3%
Operational Scheme To Provide An Additional Flood Space of 0.5 maf	97.4%	2.6%
Operational Scheme To Provide An Additional Flood Space of 1 maf	98.3%	1.7%
Structural Scheme To Increase Flood Pool by 0.7 maf	99.2%	0.8%

6.3.2. Flows Below Lake Mead and Flaming Gorge Reservoir

Figure E-3 shows the frequency distribution curves of annual, maximum monthly flows below Lake Mead (Hoover Dam), for the five operational schemes over the 1400-year study period. The frequency distribution curves are the same for the five schemes up to about the 85 percent non-exceedance level before they start to diverge, indicating that releases from Lake Mead would be the same about 85 percent of the time. The 28,000 cfs release rate observed in the figure over long percentage times corresponds to one of the flood control discharge rates from Lake Mead. Recall that

the flood control discharge rates are the forecast release levels that, if kept constant from January through July, would keep a flood control space of 1.5 maf in Lake Mead.

Figure E-4 shows the frequency distribution curves of annual, maximum monthly flows below Flaming Gorge Dam for the five operational schemes over the 1400-year study period. The capacity of the combined river and power outlet works at Flaming Gorge Dam of 7,277 cfs shows up in the figure as the flat portion of the distribution curves, from about the 88 percent to the 98 percent non-exceedance range. Releases above the 7,277 cfs level are made through the spillway. These releases occur only after the reservoir fills, and subsequent inflows exceed the combined river and power outlet capacities.

6.3.3. Upper and Lower Basin Depletions

Figure E-5 shows the frequency distribution curves of total, annual depletions in the Lower Basin for the five operational schemes over the 1400-year study. Several depletion levels can be observed from this figure, caused by the declaration of shortage, normal, or surplus conditions. The lower end of the frequency distribution curves, from the zero to about the 14 percent non-exceedance range, corresponds to those years when shortage conditions were declared in the Lower Basin. In these years, CAP deliveries were cut back by varying amounts consistent with the rules regarding a shortage condition declaration. Three depletion levels fall within this range--6.686 maf, 7.221 maf, and 7.455 maf. Depletions under normal conditions (7.816 maf) occur from about the 15 to 85 percent non-exceedance range, i.e., about 70 percent of the time. Depletions under full surplus conditions (8.473 maf), occur over varying time ranges for the five operational schemes. A transitional region between depletions at normal conditions and depletions at full surplus conditions also exist.

Figure E-5 indicates that the different flood control operational schemes at Glen Canyon Dam hardly affect Lower Basin depletions under normal, shortage or full surplus conditions. The different operational schemes affect Lower Basin depletions mostly in the transitional region between normal and full surplus conditions. In such instances, depletions under operational schemes with less storage space for flood control (or operational scheme with higher storage targets), are higher than depletions under operational schemes with more storage space for flood control (or operational scheme with lower storage targets). This happens because the higher storage targets aimed for Lake Powell makes more surplus water to be available for MWD and CAP when surplus conditions are declared.

6.3.3.2. Upper Basin Depletions

Figure E-6 shows the frequency distribution curves of total, annual depletions in the Upper Basin, for the five operational schemes over the 1400-year study period. The figure shows that the different flood control operational schemes employed at Glen Canyon Dam do not have any effect on the total annual depletions in the Upper Basin.

6.3.4. Energy Generation at Glen Canyon Dam

Figure E-7 shows the frequency distribution curves of total, annual energy generated at Glen Canyon Dam, for the five operational schemes over the 1400-year study period. The figure shows that, in this case, the energy generation is much less affected by the different flood operational schemes as indicated by the differences between the frequency distribution curves, which are very small. This is because the high depletion levels for year-2030 cause the level of Lake Powell to run below the flood

levels more often, thereby resulting in less evacuation for flood control. Table 12 gives the annual energy generated at different exceedance levels at Glen Canyon Dam for the five operational schemes over the 1400-year study period.

Table 12

Total Annual Energy Generated at Different Non-Exceedance Levels at Glen Canyon Dam over the 1400-Year Study Period, for the Five Operation Schemes, with Depletions at Year-2010 levels (units in Giga Watt Hours)

Operational Scheme	10%	25%	50%	75%	90%	1400-Yr Mean
No Flood Control Operation	4,062	4,309	4,517	5,316	6,550	4,921
Maintain Operating Policies As They Are Now	4,048	4,300	4,506	5,335	6,553	4,917
Operational Scheme To Provide An Additional Flood Space of 0.5 maf	4,039	4,288	4,493	5,365	6,503	4,903
Operational Scheme To Provide An Additional Flood Space of 1 maf	4,021	4,273	4,477	5,339	6,519	4,887
Structural Scheme To Increase Flood Pool by 0.75 maf	4,064	4,315	4,519	5,326	6,543	4,923

6.3.5. Salt Concentration Below Lake Mead

Figure E-8 shows the frequency distribution curves of annual salt concentration below Lake Mead, for the five operational schemes over the 1400-year study period. The figure shows that salt concentration below Lake Mead is not influenced by the different flood control operational schemes at Glen Canyon Dam.

6.3.6. Storage Contents and Surface Area of Lake Powell

Figures E-9 and E-10 show the frequency distribution curves of storage contents and surface areas of Lake Powell, for the five operational schemes over the 1400-year study period. The figures show that surface areas and storage contents for operational schemes with no-flood control, and with the structural measure are about the same for the most part--and are more than the storage areas and storage contents for the other three operational schemes. The least surface areas and storage contents occur under the operational scheme with the 1 maf additional flood control space.

6. CONCLUSIONS

The results from this study indicate that the flood control operational schemes examined at Glen Canyon Dam will decrease the frequency and magnitude of flood flows below the dam. Their efficiencies (percent reduction in floods compared with the no-flood control measure), however, are reduced as depletions in the Colorado River Basin increases. This is because increased depletions act as a flood control mechanism since more water is consumptively used and less water is stored in the

reservoirs. Thus, the percentage of time when the flood control targets are invoked is reduced. A summary of flood occurrence probabilities under the five operational schemes for the three depletion levels is given in Table 13.

Table 13

Flood Occurrence Percentages for the Five Operational Schemes under Depletion Levels in Years 1991, 2010, and 2030

Operational Scheme	Probability of Flood Occurrence (Percent)		
	Year-1991 Depletion Level	Year-2010 Depletion Level	Year-2030 Depletion Level
No Flood Control Operation	11.1	6.4	5.8
Maintain Operating Policies As They Are Now	6.8	3.6	3.3
Operational Scheme To Provide An Additional Flood Space of 0.5 maf	5.6	2.7	2.6
Operational Scheme To Provide An Additional Flood Space of 1 maf	3.8	1.9	1.7
Structural Scheme To Increase Flood Pool by 0.75 maf	4.3	1.9	0.8

In general, the non-structural flood control measures (specifically, providing an additional 1 maf flood control space) could reduce the frequency of excessive releases or flood flows by roughly half, compared to the current flood operational scheme.

In the very extreme inflow years, which were less than 1 percent of the 1400-year study period, none of the operational schemes could effectively mitigate the magnitude of flood flows below Glen Canyon Dam because flows in these years were simply too much for the system to handle.

The five flood control operational schemes considered had no effect on Upper Basin depletions. They also had insignificant affects on Lower Basin depletions, except in transitional circumstances where surplus conditions were declared in the Lower Basin but the amount of water from the surplus was not enough for a full supply. In such a situation, only depletions for MWD and CAP--the two entities that take surplus deliveries--were affected.

The different flood control operational schemes did not have any apparent effect on salt concentration below Lake Mead. They also had insignificant effects on reservoir releases in the Upper Basin (represented by releases from Flaming Gorge Dam). Reservoir releases in the Lower Basin (represented by flows below Lake Mead), however, were affected by flood control operational schemes at Glen Canyon Dam. At flows beneath the flood control discharge rate of 28,000 cfs at Lake Mead (the 28,00 cfs discharge rate is one of the six standard flood discharge rates at Lake Mead), flows below Lake Mead were lower in schemes with some flood control than in the no-flood control scheme. After releases from Lake Mead surpassed this discharge rate, flows were higher in the schemes with some flood control than in the no-flood control scheme, except for the flood control scheme with the structural measure, which had lower flows at all times.

Generally, more energy was generated in operational schemes with some flood control measure during drier years, while less energy was generated in the wetter years, when compared to the no-flood control operational scheme. By the time depletions were at year-2030 levels, however, the different flood operational schemes had little effect on the amount of energy generated, because the high depletion levels for year-2030 caused the level of Lake Powell to run below the flood levels more often, thereby resulting in less evacuation for flood control. Overall, the most energy was generated under the operational scheme with the structural measure because of the increased storage capacity, which reduces spills while allowing higher reservoir levels that results in higher hydraulic heads for generating power. This study did not consider the relative value of generated energy, e.g., peaking vs. baseload; and how the operations at Glen Canyon Dam could be optimized for maximum energy generation within the framework of the flood control operational schemes examined. To do this will require connecting a full scale energy dispatch model (e.g., ELFIN) to the CRM; this is suggested as a direction for future studies. Careful design of the protocol for evacuation of flood control space could allow for increased peaking capacity, and thus a greater value for hydroelectric operations, as compared to a protocol where evacuation is accomplished as rapidly as possible.

The flood control operational schemes impacted Lake Powell reservoir content and surface area. The impacts were felt in the form of reduced contents and surface areas. The more effective the flood control operational scheme had in reducing the flood frequency, the greater reduction in Lake Powell surface area and content occurred.

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APPENDIX A

A.1 INTRODUCTION

The limitations of using a model with a monthly time step to study the frequencies and magnitudes of floods is addressed in this Appendix. A model with a monthly time step is unlikely to capture all information related to a flood study because floods occur over a range of time steps, some of which are shorter than one month. Flood durations could be on the order of days or hours; durations on the order of minutes (e.g., flash floods) are also possible.

Streamflow locations that experience little or no influence from upstream reservoirs are expected to experience a lot of floods that have short durations. However, one would expect streamflow locations with considerable influence from an upstream reservoir to have fewer floods but with longer durations. This is because operations of the upstream reservoir to temporarily store high inflows until they can be discharged without flooding, will reduce the number of floods and prolong the duration of those that do occur. Hence, flood durations at locations with an upstream reservoir--especially at locations that have reservoirs with very large storage capacities---will typically last over several days, thereby allowing a model with a monthly time step to perceive such floods.

The location for this study is below Glen Canyon Dam, which forms Lake Powell--a reservoir with a storage capacity of 24.322 maf. Hence, it is expected that operations at the dam will modulate river discharges since Lake Powell is operated to control floods below the dam. The reservoir operations will reduce the variation of daily flows about the mean monthly flow and remove sharp spikes from the outflow hydrology, thereby reducing the number of floods with short durations. Those floods that do occur below the dam will be of longer durations, lasting over several days; hence, a model with a monthly time step should be able to adequately quantify such floods within reasonable limits.

To see if the above hypothesis is tenable and thereby verify the adequacy of the monthly model used for this study, we examined the statistics of daily and monthly recorded flows at the USGS station below Glen Canyon Dam, at Lees Ferry. Though inflows from the Paria River enter the Colorado River between the dam and above the streamflow gage at Lees Ferry, thereby showing up in the recorded flow at Lees Ferry, we have ignored their effects in this analysis because their relative magnitude compared to releases from Lake Powell is very small.

The statistics examined were mean, monthly flow, and maximum flow within each month over the period from October 1921 to September 1991. This period covers three intervals: (a) the pre-dam period from 1921-1962, (b) the interval when the dam was filling from 1963-1980, and (c) the interval after the dam filled for the first time from 1981-1991.

A flood flow was defined as flow above 33,200 cfs, the capacity of the power outlet works at Glen Canyon Dam. Two variables were used for quantifying the flood flows: a) the number of flood occurrences; and b) the magnitude of the flood flows above the threshold level.

Number or Frequency of Flood Occurrences

The number of months that a model with a monthly time step will "see" a flood was compared to the number of months that a daily model will "see" a flood during the three time periods defined above. A monthly model is defined to "see" a flood when the mean monthly flow is above 33,200 cfs-days, and a daily model is defined to "see" a flood when the maximum daily flow within the month is greater than 33,200 cfs-days.

Any month that has a mean monthly flow higher than 33,200 cfs will also have a maximum daily flow in the month to be higher than 33,200 cfs. However, the converse is not always true. It is possible for the mean monthly flow to be lower than 33,200 cfs while the maximum daily flow in the month is higher than 33,200 cfs. If the latter happens quite often, then a monthly model will be inadequate for studding the frequency of flood flows because the mean monthly flow statistic will not detect a flood, whereas, the maximum daily flow in-the-month statistic will detect the flood. However, if the former predominates, a monthly model should be okay for the flood impact study.

The above is illustrated in Figure A.1, which shows a plot of the daily and mean monthly flows for Water Year 1984 (October 1983 to September 1984). The threshold value of 33,200 cfs-days is also shown in the figure. It can be observed from the figure that, for the three month period from May through July, both the mean monthly and maximum daily flows are above 33,200 cfs. In these months, both a monthly and a daily model will "see" the floods that occurred. However, in August, the monthly mean flow is below the threshold value while the daily maximum flow for the month is above the threshold value. In this case, a daily model will "see" a flood for the month while a monthly model will not "see" any flood.

The summary from this analysis for the three periods is given in the following table.

	Pre-Dam Period 1921 - 1962	Filling Period 1963 - 1980	Post Filling Period 1981 - 1991
Number of months with maximum daily flow in higher than 33,200 cfs	126 (100%)	5 (100%)	11 (100%)
Number of months with mean monthly flow higher than 33,200 cfs	64 **(51%)**	2 **(40%)**	9 **(82%)**
Number of months with mean monthly lower than 33,200 cfs	62 (49%)	3 (60%)	2 (18%)

The above analysis shows that, after the dam was constructed and filled once, a monthly model will predict a flood 82% of the time that a daily model predicts the flood compared to 51% of the time if no dam exists. Since the model assumptions assume present conditions, we can conclude from this

simple analysis that a monthly model will correctly count the number of flood occurrences 82% of the time.

The definition of a flood occurrence used in the frequency analysis reported in this study counts a flood when the maximum, mean monthly flow in the year is above 33,200 cfs. That is, a flood is said to have occurred in a year if the mean monthly flow in any month within the year exceeds 33,200 cfs. Hence, a monthly model will "see" a flood if the annual, maximum, mean monthly flow is greater than 33,200 cfs, while a daily model will "see" a flood if the annual, maximum, daily flow is greater than 33,200 cfs. If this definition is applied to the recorded data, the percentage of time that a monthly model will "see" a flood compared to the daily model will be higher still than what is shown above.

Flood Magnitude

The flood magnitude is defined as the excess flow above the 33,200 cfs threshold value. This definition is used to compute the total flood magnitude over each of the three periods, using daily and monthly time intervals. Hence, a flood magnitude using a daily time step over a particular period is computed as the sum of the differences between the recorded daily flows, and 33,200 cfs-days--when the daily flows exceed 33,200 cfs-days. Likewise, the magnitude of flood flows for the monthly time interval is computed as the sum of the differences between the monthly, mean flows, and 33,200 cfs-days--when the monthly, mean flows exceed 33,200 cfs-days. A summary of the results for the three time periods is given below.

Pre-Dam Period, 1921-62

Magnitude of flood flows from daily interval	=	104.40 maf
Magnitude of flood flows from a monthly interval	=	92.47 maf
% of monthly flow to daily flow	=	89%

Filling Period, 1963-1980

Magnitude of flood flows from daily interval	=	1.06 maf
Magnitude of flood flows from a monthly interval	=	0.59 maf
% of monthly flow to daily flow	=	56%

Post-Filling Period, 1981-1991

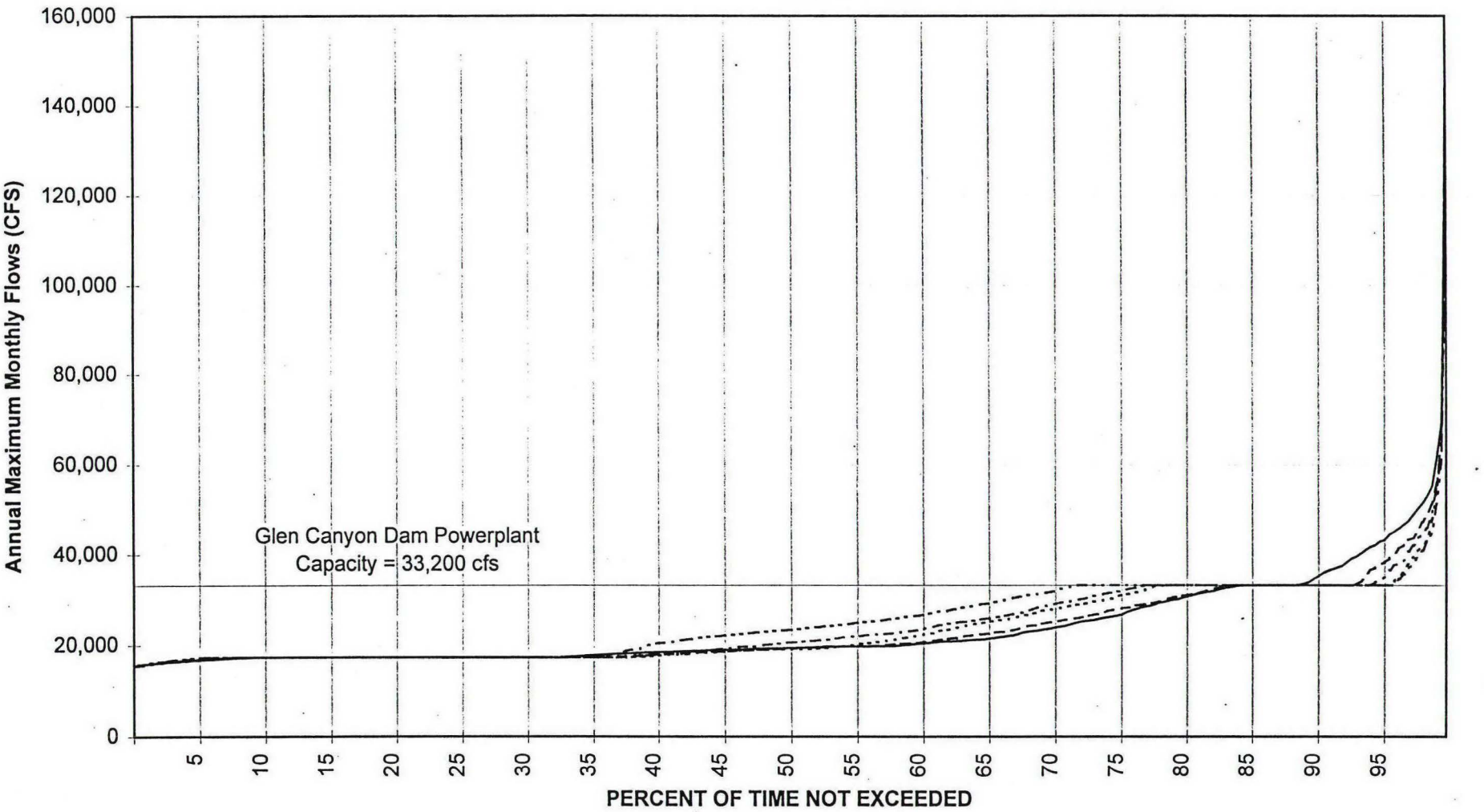
Magnitude of flood flows from daily interval	=	6.04 maf
Magnitude of flood flows from a monthly interval	=	5.22 maf
% of monthly flow to daily flow	=	87%

The above analysis shows that, during the pre-dam and post-filling periods, a monthly model will predict the magnitude of flood flows quit well when compared to predictions from a daily model (89% and 87%, respectively), but the predictions will not be good during the filling period.

Figure C-1

Frequency Distribution Curves of Maximum, Monthly Flow Below Glen Canyon Dam in Each Year of the 1400-Year Study Period for the Five Operational Schemes

With Year-1991 Depletion Level

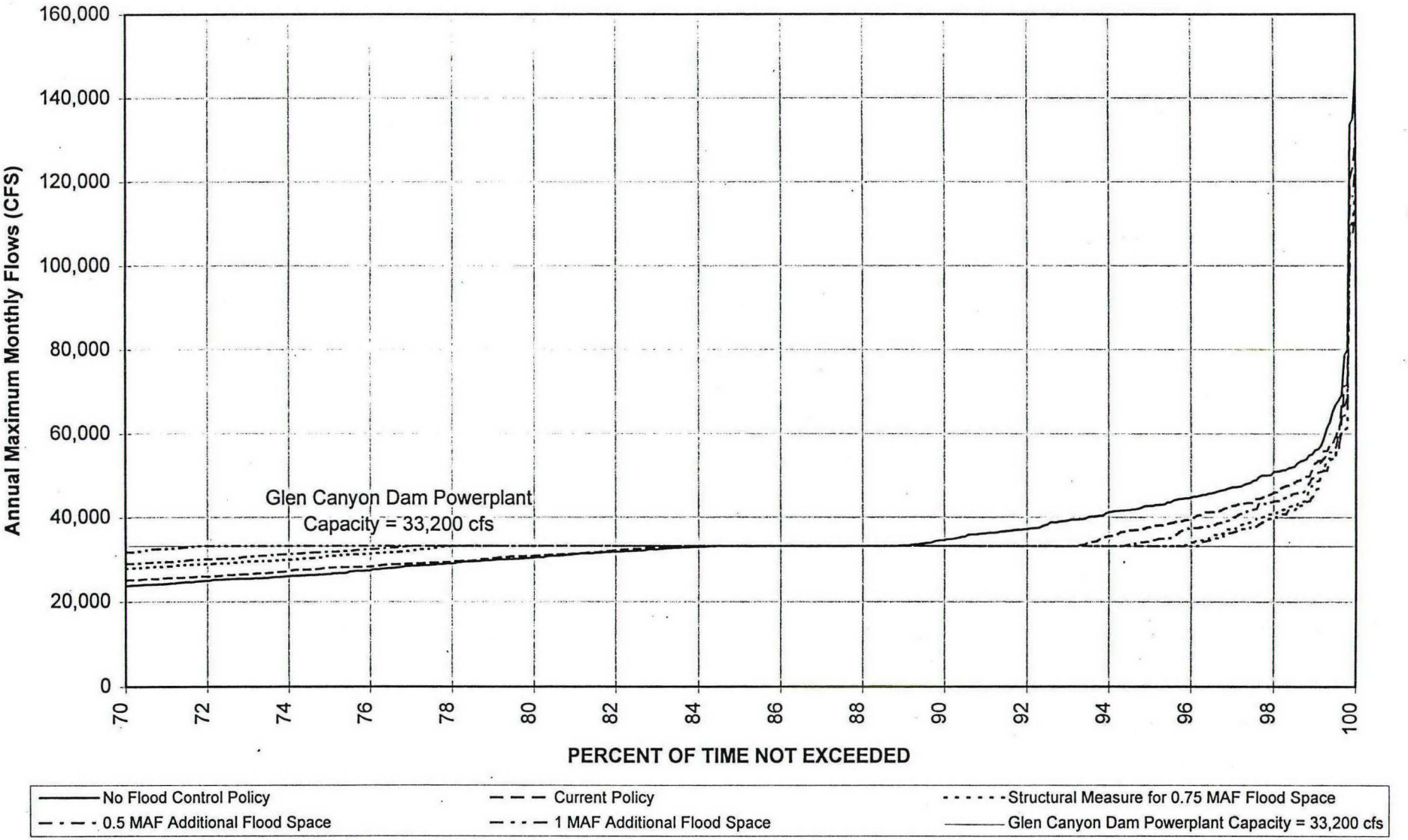


LAST UPDATED Scenario 0: 1/16/95 11:16am Scenario 1: 1/16/95 11:19am Scenario 2: 1/16/95 11:23am Scenario 3: 1/16/95 11:27am Scenario 4: 1/16/95 11:31am

Figure C-2

Expanded Section of the Frequency Distribution Curves in Figure C-1 Showing the Tail Sections

With Year-1991 Depletion Level

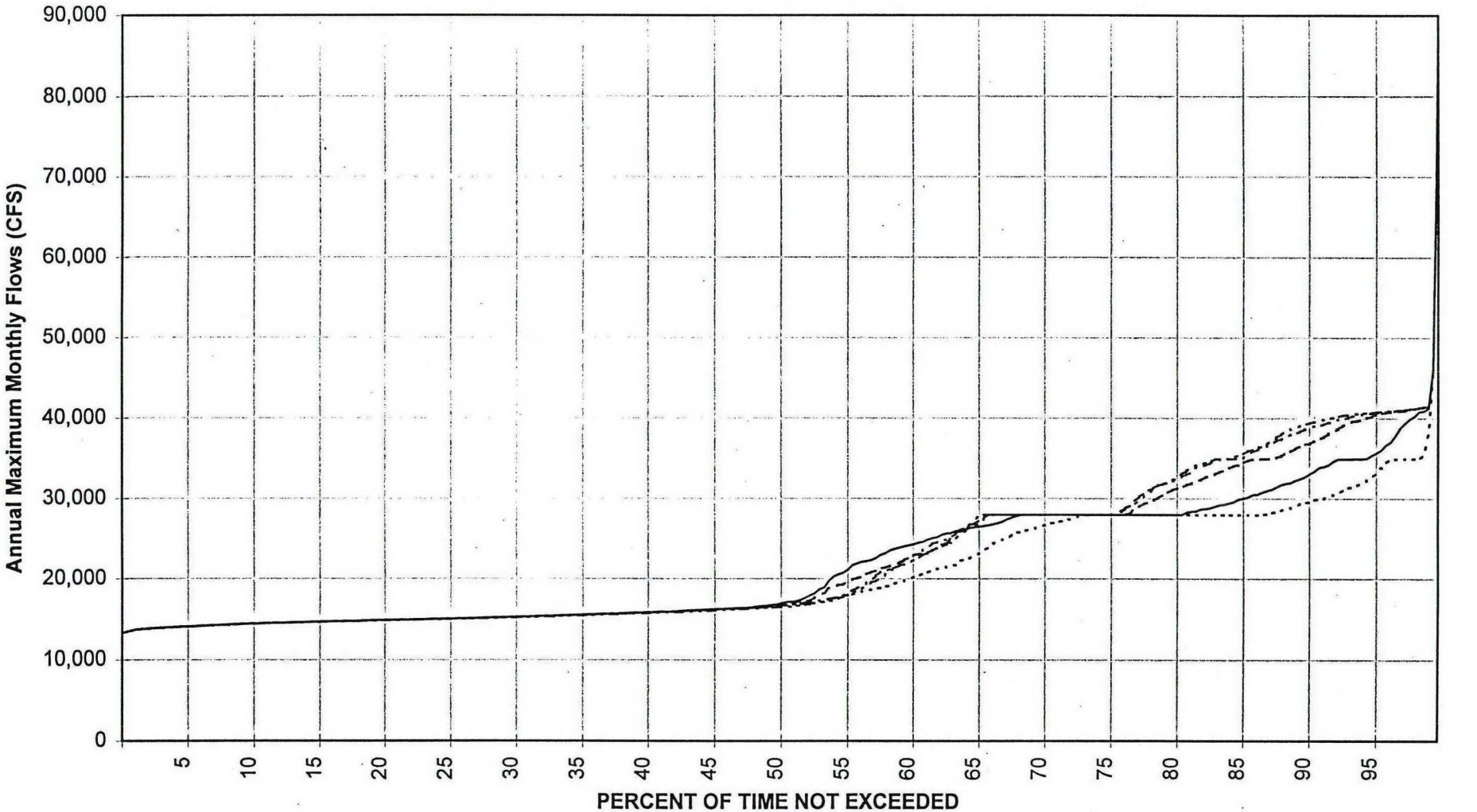


LAST UPDATED Scenario 0: 1/16/95 11:16am Scenario 1: 1/16/95 11:19am Scenario 2: 1/16/95 11:23am Scenario 3: 1/16/95 11:27am Scenario 4: 1/16/95 11:31am

Figure C-3

Frequency Distribution Curves of Maximum, Monthly Flows Below Lake Mead in Each Year of the 1400-Year Study Period for the Five Operational Schemes

With Year-1991 Depletion Level

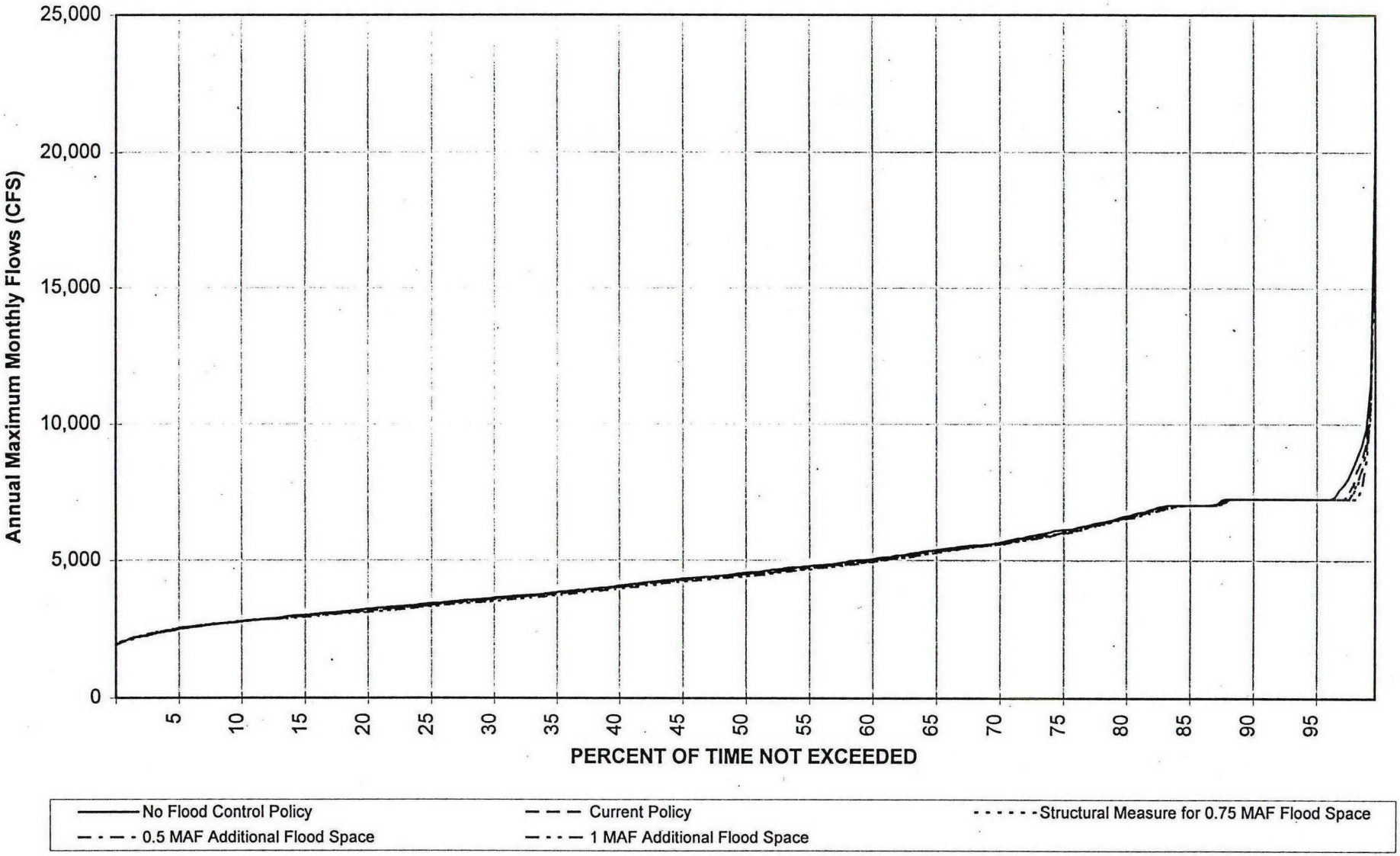


LAST UPDATED Scenario 0: 1/16/95 11:16am · Scenario 1: 1/16/95 11:20am Scenario 2: 1/16/95 11:24am Scenario 3: 1/16/95 11:28am Scenario 4: 1/16/95 11:31am

Figure C-4

Frequency Distribution Curves of Maximum Monthly Flow Below Flaming Gorge Dam in Each Year of the 1400-Year Study Period for the Five Operational Schemes

With Year-1991 Depletion Level

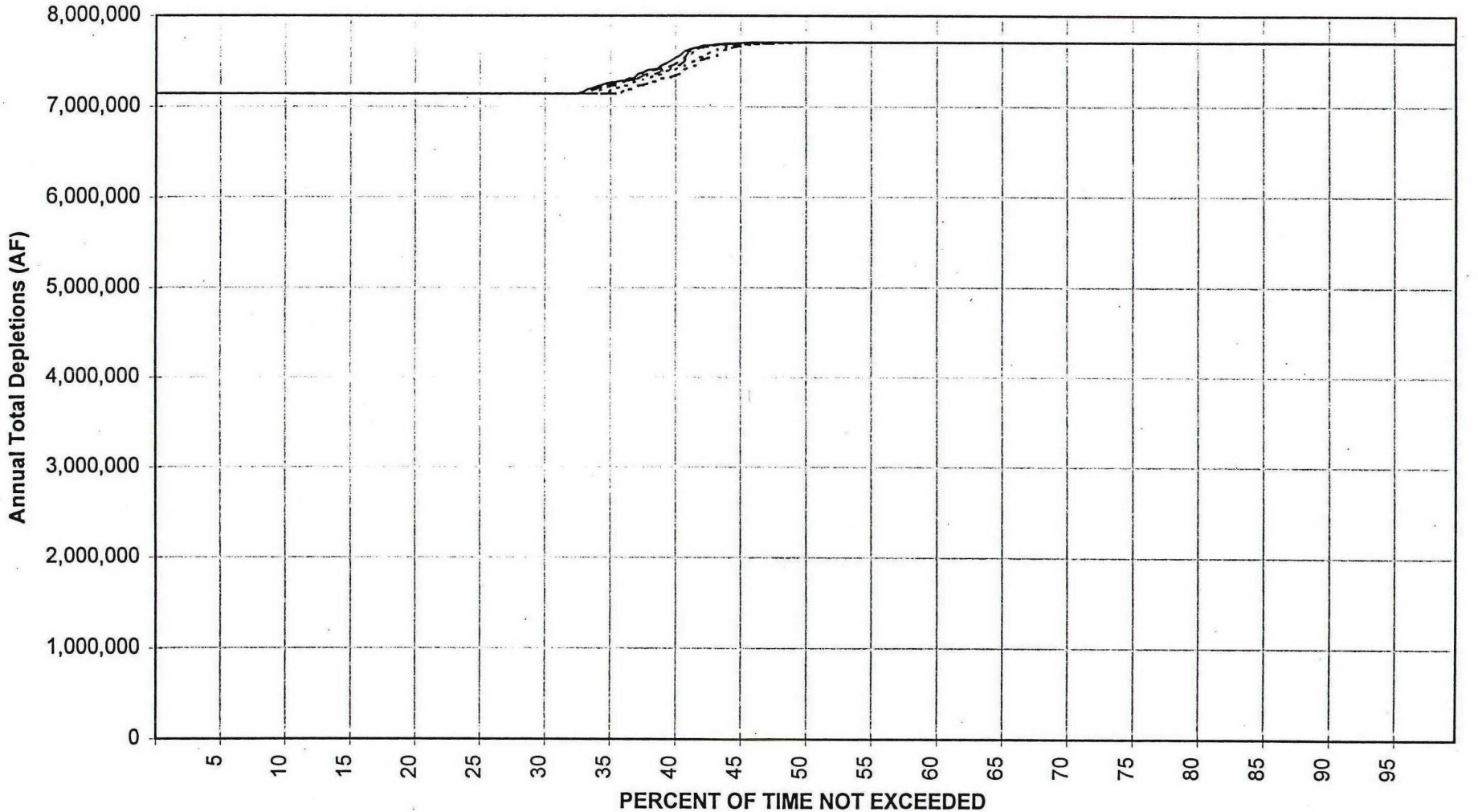


LAST UPDATED Scenario 0: 1/16/95 11:16am Scenario 1: 1/16/95 11:20am Scenario 2: 1/16/95 11:24am Scenario 3: 1/16/95 11:28am Scenario 4: 1/16/95 11:32am

Figure C-5

Frequency Distribution Curves of Lower Basin Total Annual Depletions from the 1400-Year Study Period for the Five Operational Studies

With Year-1991 Depletion Level

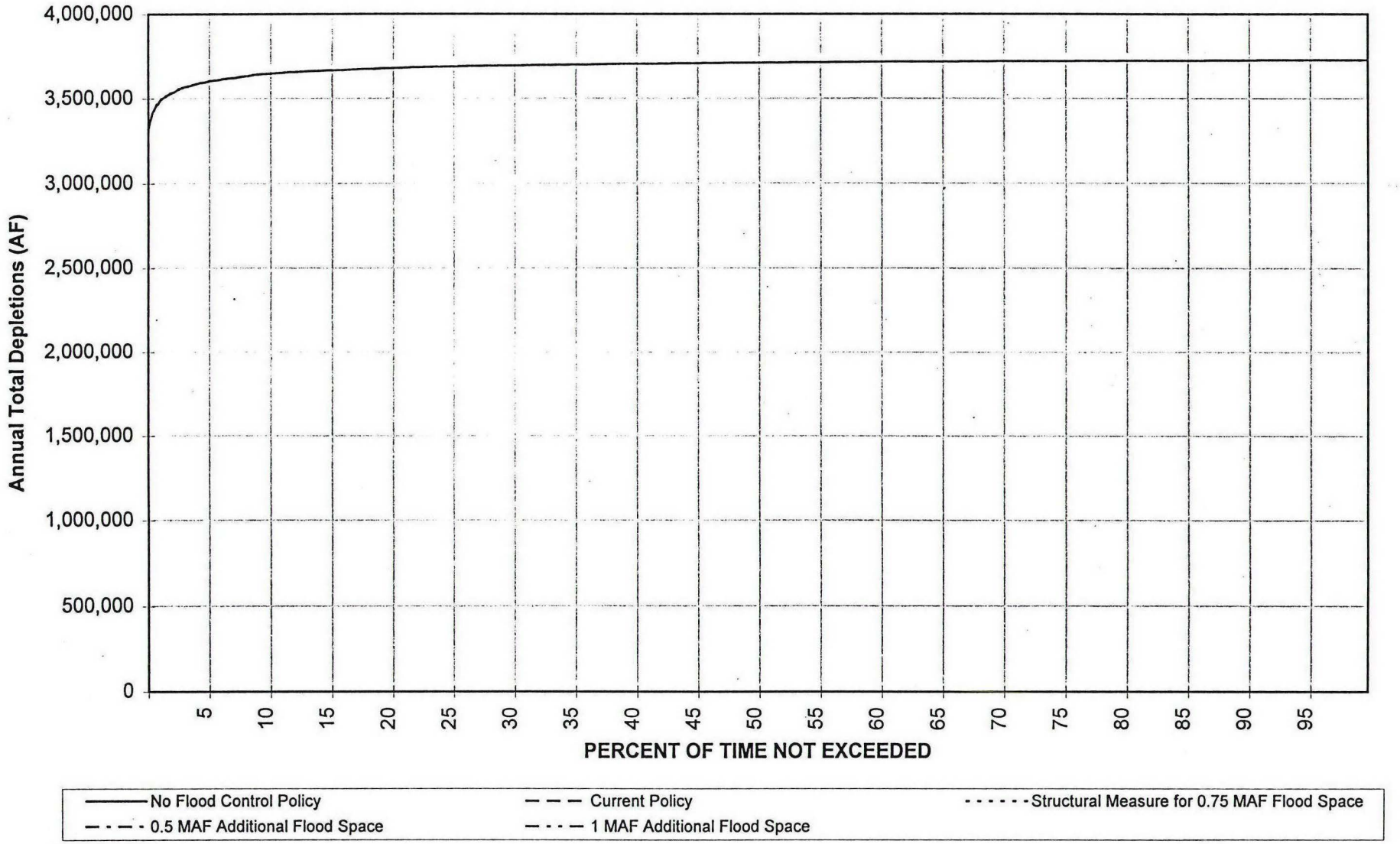


LAST UPDATED Scenario 0: 1/16/95 11:17am Scenario 1: 1/16/95 11:21am Scenario 2: 1/16/95 11:24am Scenario 3: 1/16/95 11:28am Scenario 4: 1/16/95 11:32am

Figure C-6

Frequency Distribution Curves of Upper Basin Total Annual Depletions from the 1400-Year Study Period for the Five Operational Schemes

With Year-1991 Depletion Level

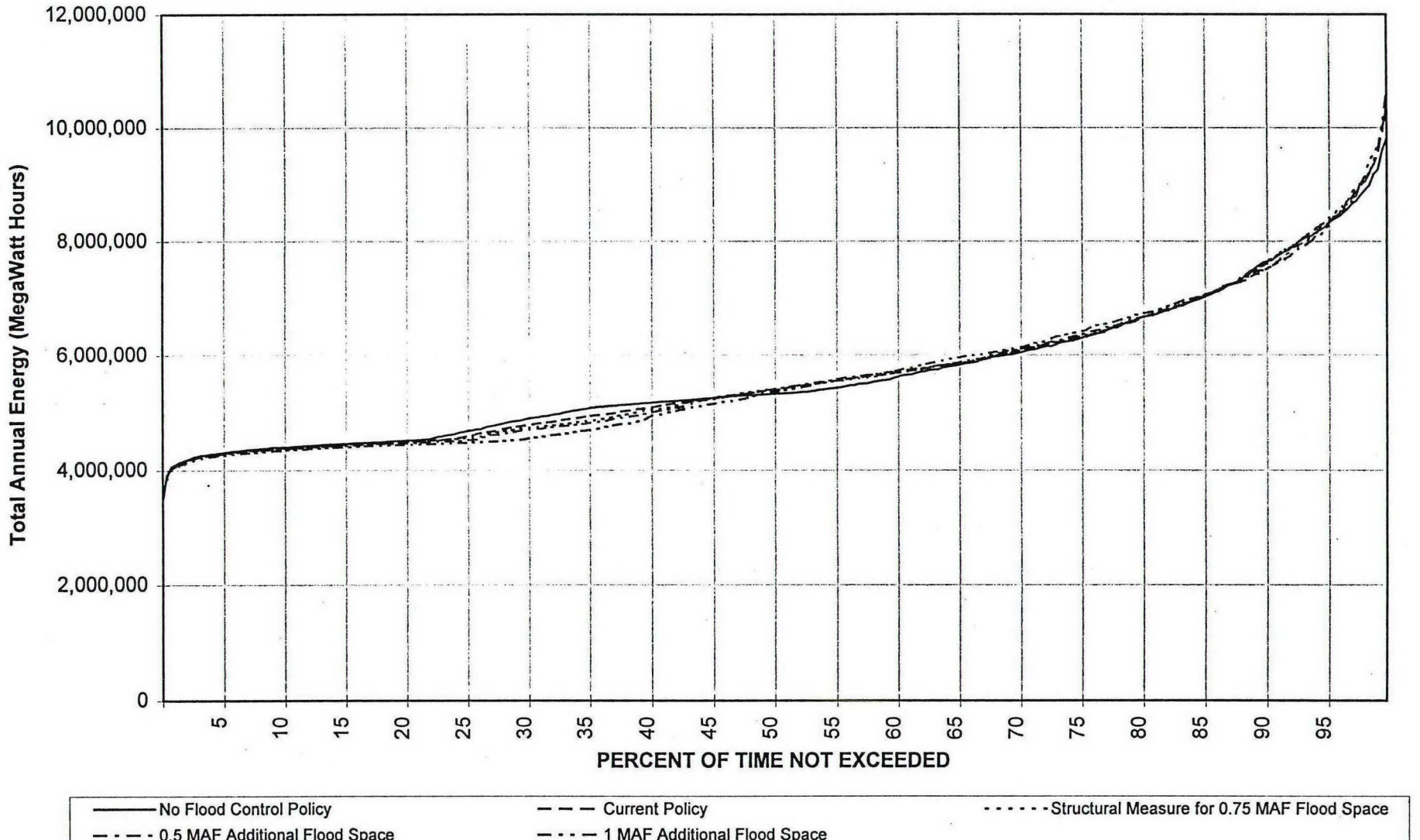


LAST UPDATED Scenario 0: 1/16/95 11:17am Scenario 1: 1/16/95 11:21am Scenario 2: 1/16/95 11:25am Scenario 3: 1/16/95 11:29am Scenario 4: 1/16/95 11:33am

Figure C-7

Frequency Distribution Curves of Annual Total Energy Generated at Glen Canyon Dam from the 1400-Year Study Period for the Five Operational Schemes

With Year-1991 Depletion Level

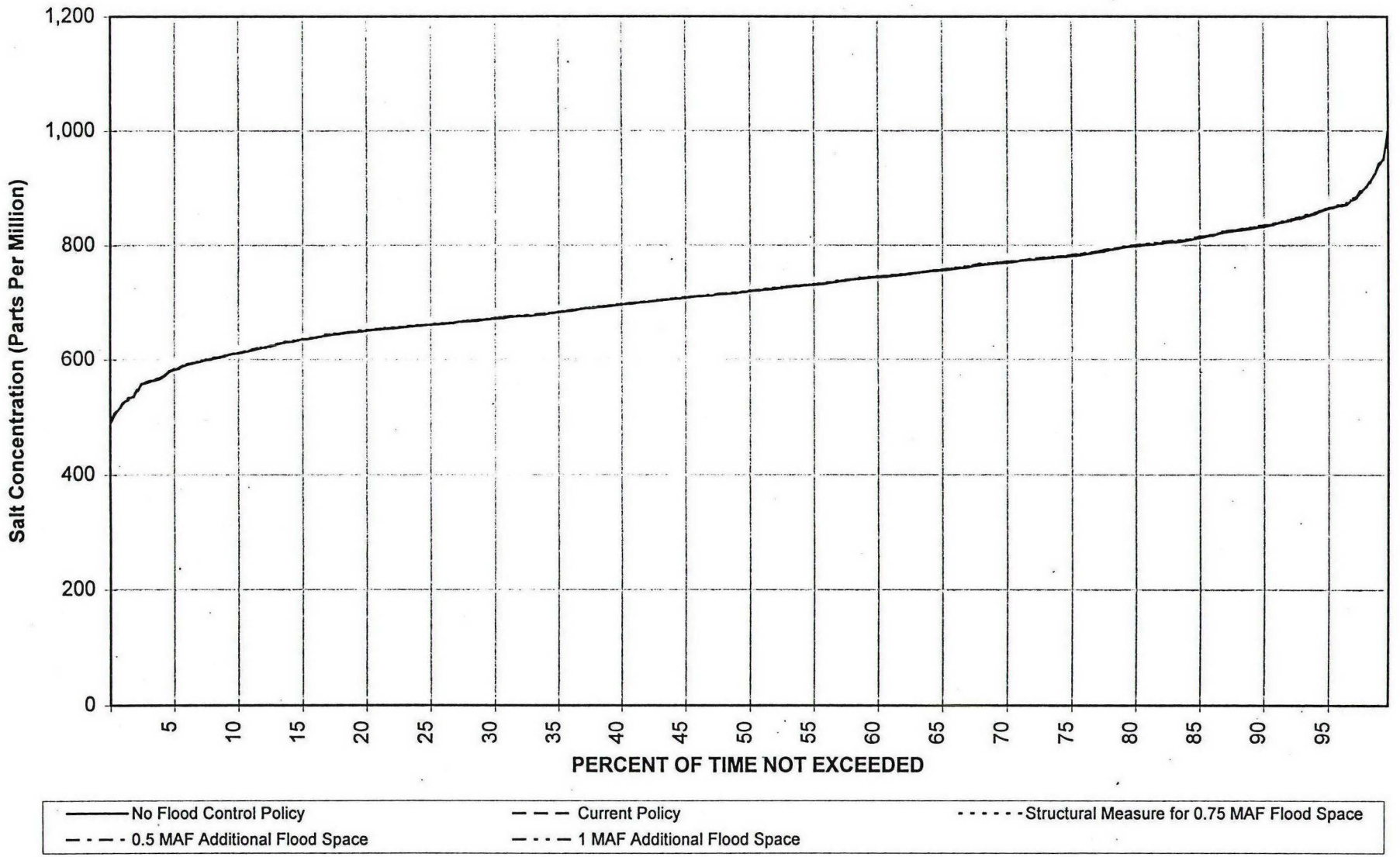


LAST UPDATED Scenario 0: 1/16/95 11:17am Scenario 1: 1/16/95 11:21am Scenario 2: 1/16/95 11:25am Scenario 3: 1/16/95 11:29am Scenario 4: 1/16/95 11:33am

Figure C-8

Frequency Distribution Curves of Annual Salt Concentration Below Lake Mead from the 1400-Year Study Period for the Five Operational Schemes

With Year-1991 Depletion Level

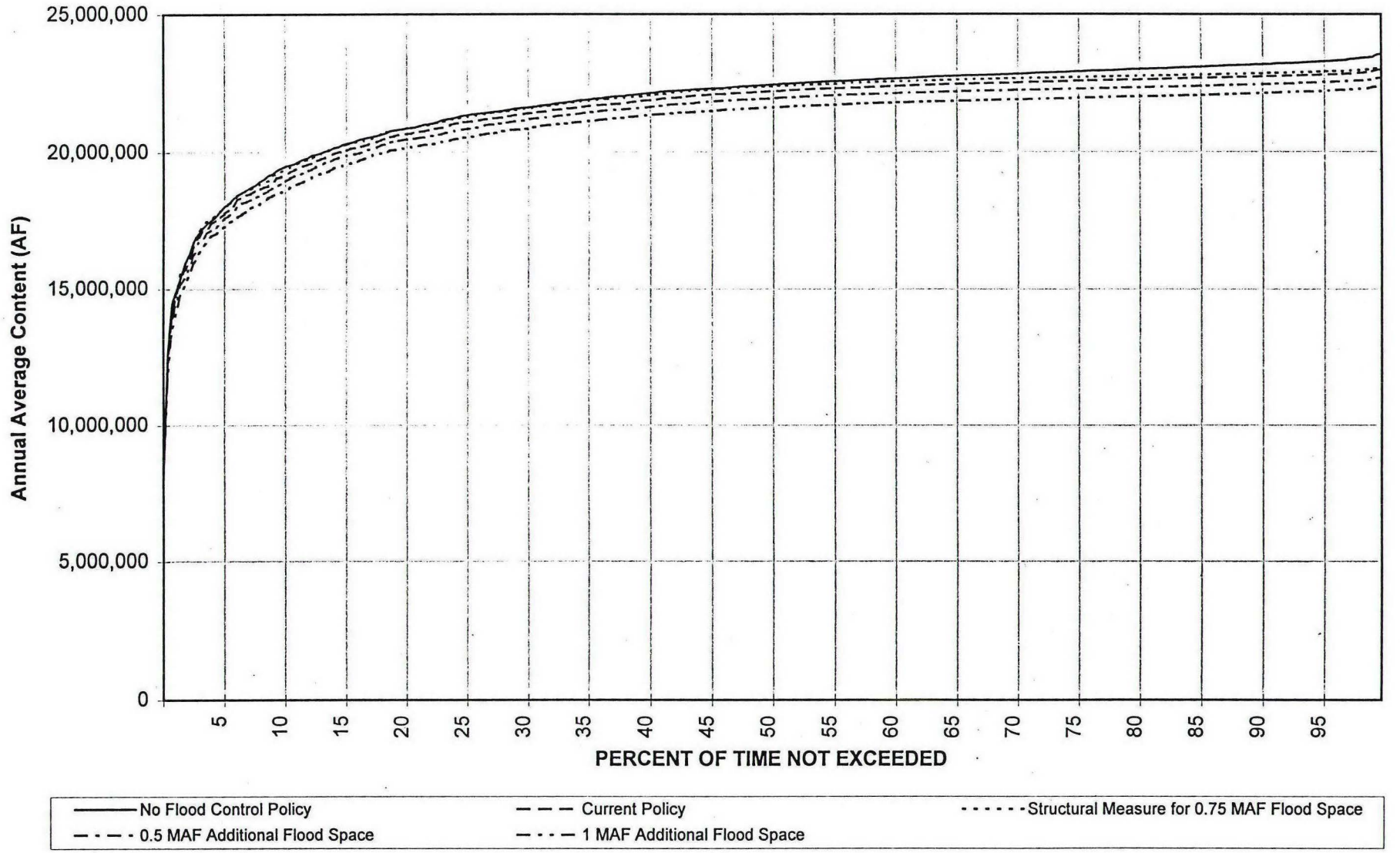


LAST UPDATED Scenario 0: 1/16/95 11:18am Scenario 1: 1/16/95 11:22am Scenario 2: 1/16/95 11:26am Scenario 3: 1/16/95 11:29am Scenario 4: 1/16/95 11:33am

Figure C-9

Frequency Distribution Curves of Average Annual Storage Contents at Lake Powell from the 1400-Year Study Period for the Five Operational Schemes

With Year-1991 Depletion Level

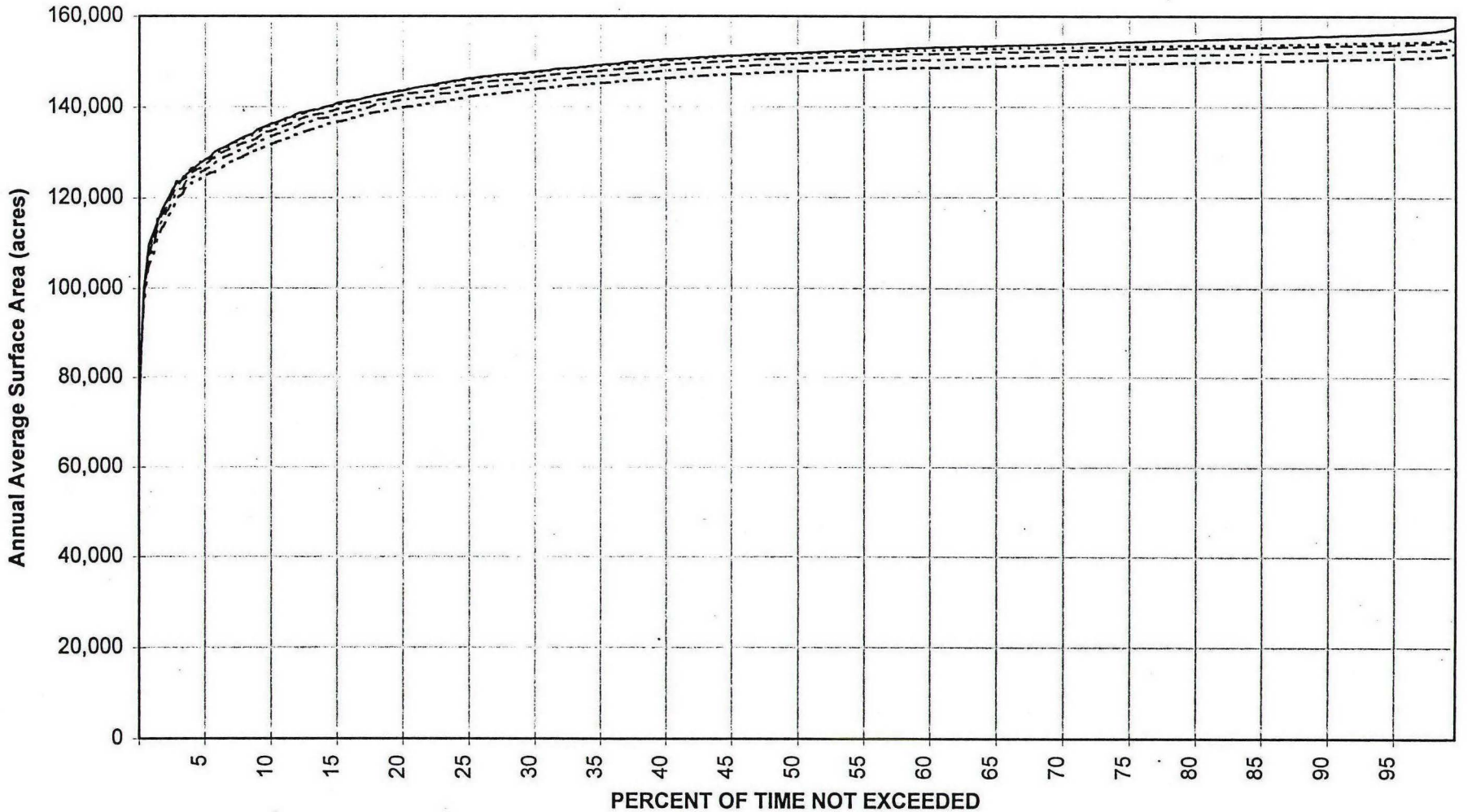


LAST UPDATED Scenario 0: 1/16/95 11:18am Scenario 1: 1/16/95 11:22am Scenario 2: 1/16/95 11:26am Scenario 3: 1/16/95 11:30am Scenario 4: 1/16/95 11:34am

Figure C-10

Frequency Distribution Curves of Average AnnualReservoir Surface Area at Lake Powell in Each Year from the 1400-Year Study Period for the Five Operational Schemes

With Year-1991 Depletion Level

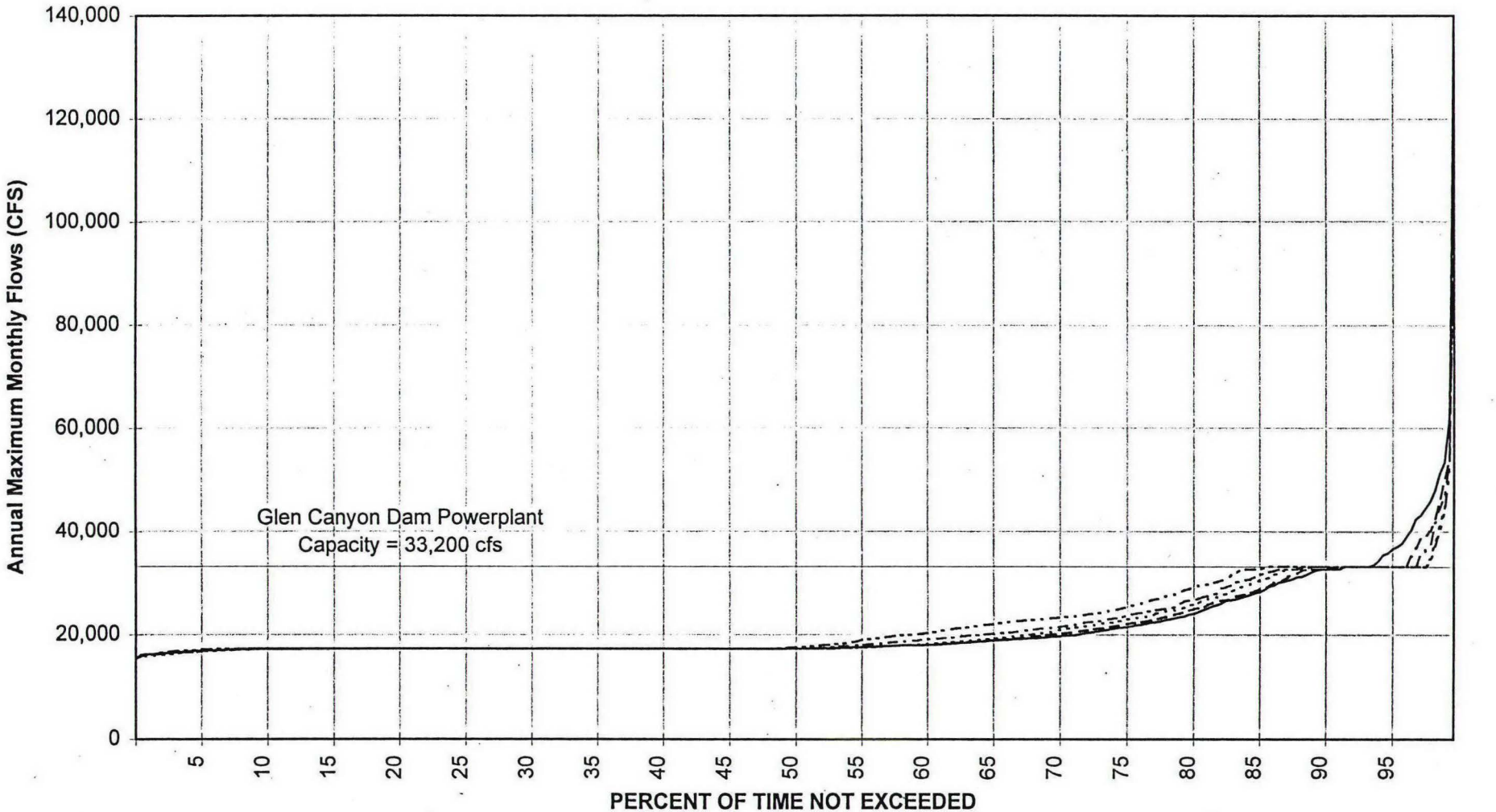


LAST UPDATED 1/16/95 11:34am Scenario 0: 1/16/95 11:18am Scenario 1: 1/16/95 11:22am Scenario 2: 1/16/95 11:26am Scenario 3: 1/16/95 11:30am Scenario 4:

Figure D-1

Frequency Distribution Curves of Maximum, Monthly Flow Below Glen Canyon Dam in Each Year of the 1400-Year Study Period for the Five Operational Schemes

With Year-2010 Depletion Level

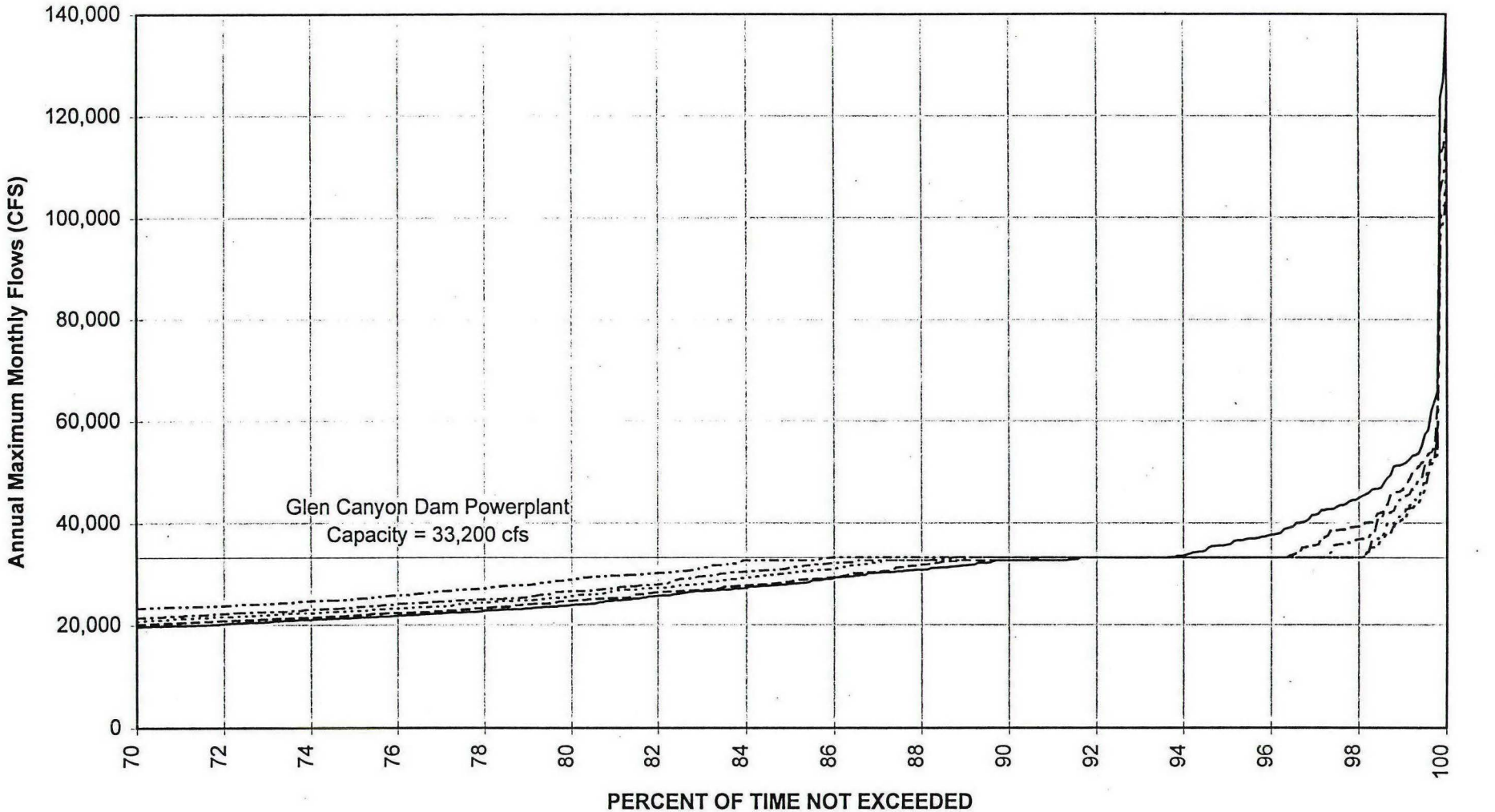


LAST UPDATED Scenario 13: 4/6/95 03:21pm Scenario 5: 4/6/95 03:25pm Scenario 6: 4/6/95 03:28pm Scenario 7: 4/6/95 03:32pm Scenario 8: 4/6/95 03:36pm

Figure D-2

Expanded Section of the Frequency Distribution Curves in Figure D-1 Showing the Tail Sections

With Year-2010 Depletion Level

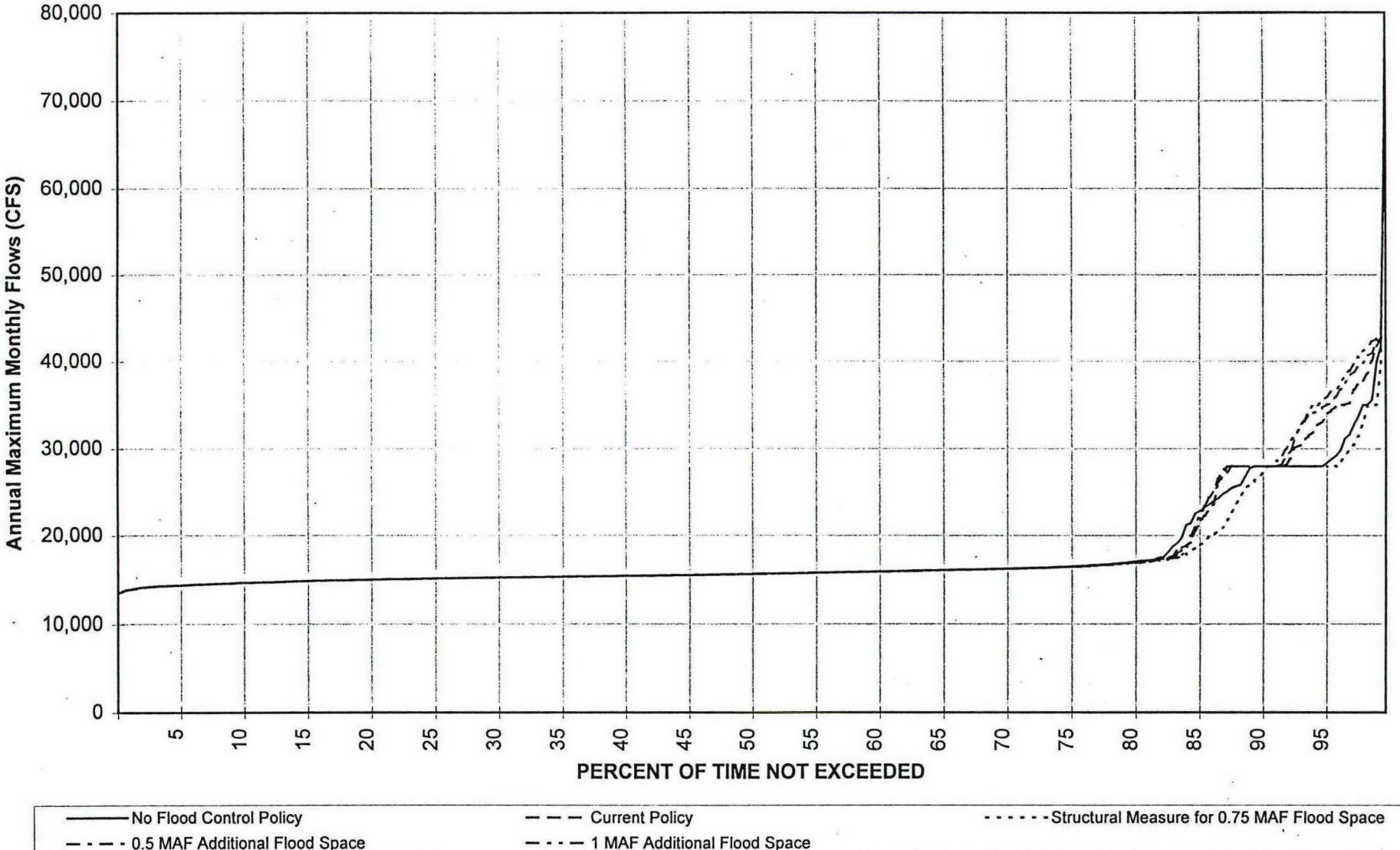


LAST UPDATED Scenario 13: 4/6/95 03:21pm Scenario 5: 4/6/95 03:25pm Scenario 6: 4/6/95 03:28pm Scenario 7: 4/6/95 03:32pm Scenario 8: 4/6/95 03:36pm

Figure D-3

Frequency Distribution Curves of Maximum, Monthly Flows Below Lake Mead in Each Year of the 1400-Year Study Period for the Five Operational Schemes

With Year-2010 Depletion Level

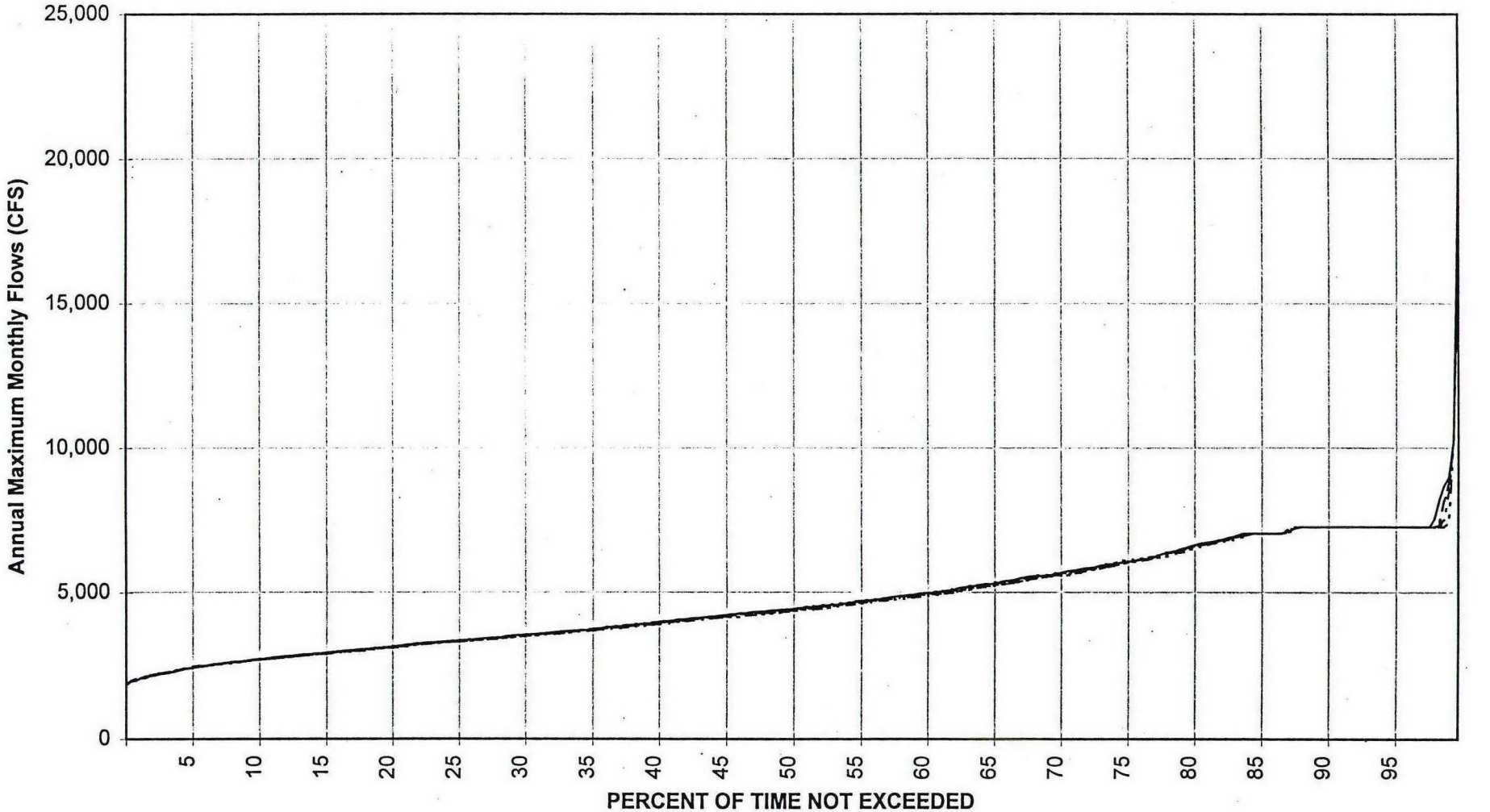


LAST UPDATED Scenario 13: 4/6/95 03:22pm Scenario 5: 4/6/95 03:25pm Scenario 6: 4/6/95 03:29pm Scenario 7: 4/6/95 03:33pm Scenario 8: 4/6/95 03:36pm

Figure D-4

Frequency Distribution Curves of Maximum Monthly Flow Below Flaming Gorge Dam in Each Year of the 1400-Year Study Period for the Five Operational Schemes

With Year-2010 Depletion Level

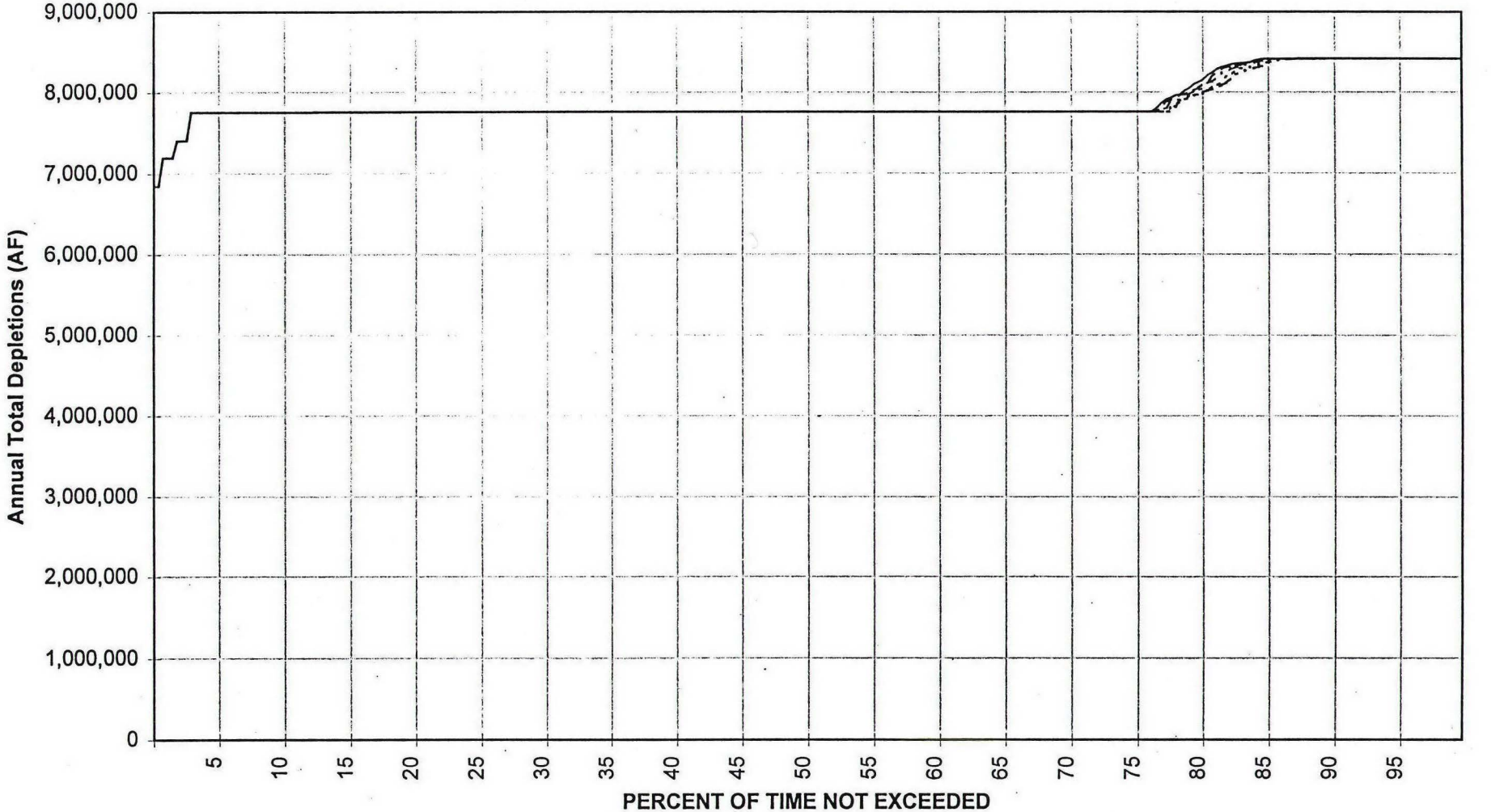


LAST UPDATED Scenario 13: 4/6/95 03:22pm Scenario 5: 4/6/95 03:26pm Scenario 6: 4/6/95 03:29pm Scenario 7: 4/6/95 03:33pm Scenario 8: 4/6/95 03:37pm

Figure D-5

Frequency Distribution Curves of Lower Basin Total, Annual Depletions from the 1400-Year Study Period for the Five Operational Studies

With Year-2010 Depletion Level

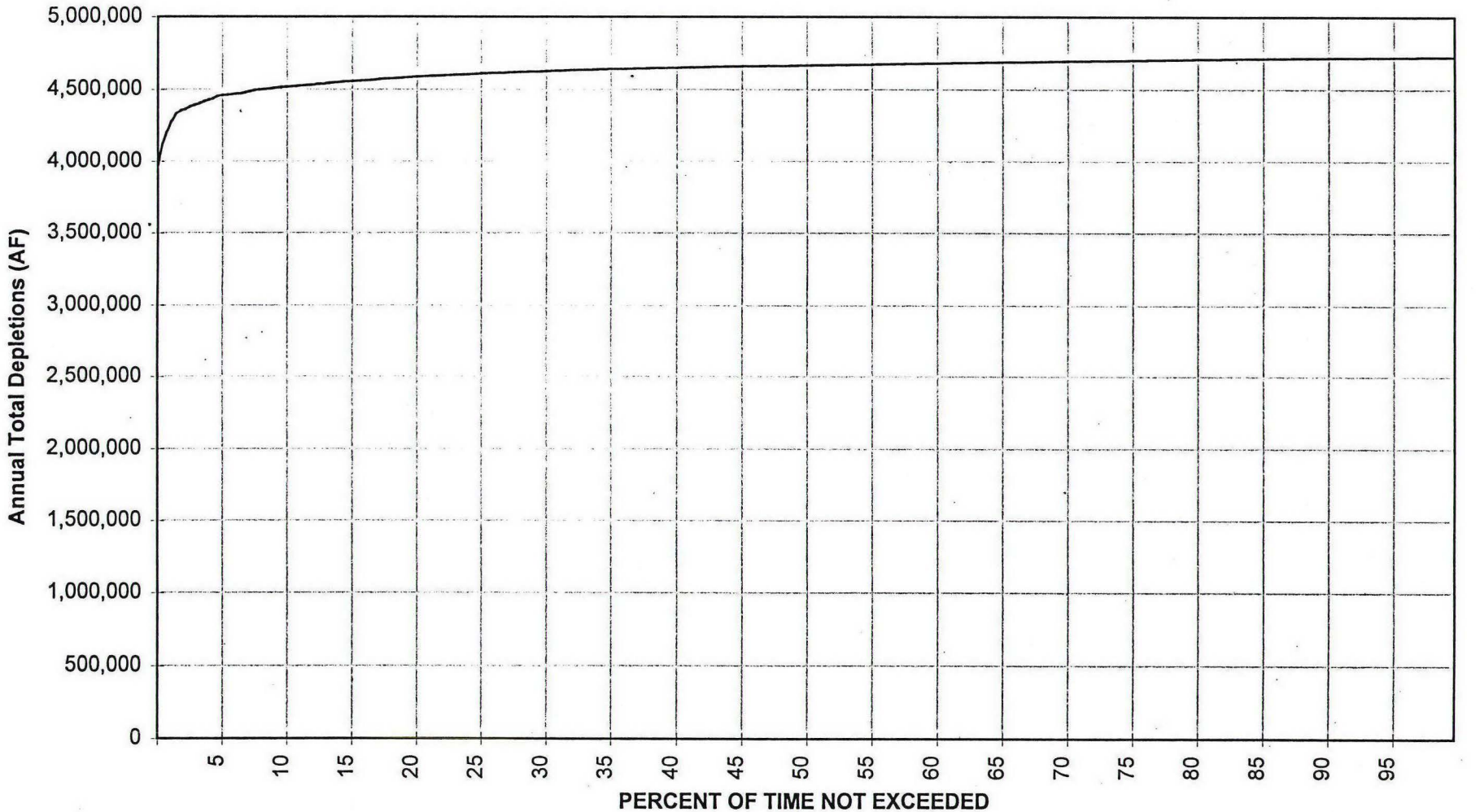


LAST UPDATED Scenario 13: 4/6/95 03:22pm Scenario 5: 4/6/95 03:26pm Scenario 6: 4/6/95 03:30pm Scenario 7: 4/6/95 03:33pm Scenario 8: 4/6/95 03:37pm

Figure D-6

Frequency Distribution Curves of Upper Basin Total, Annual Depletions from the 1400-Year Study Period for the Five Operational Schemes

With Year-2010 Depletion Level

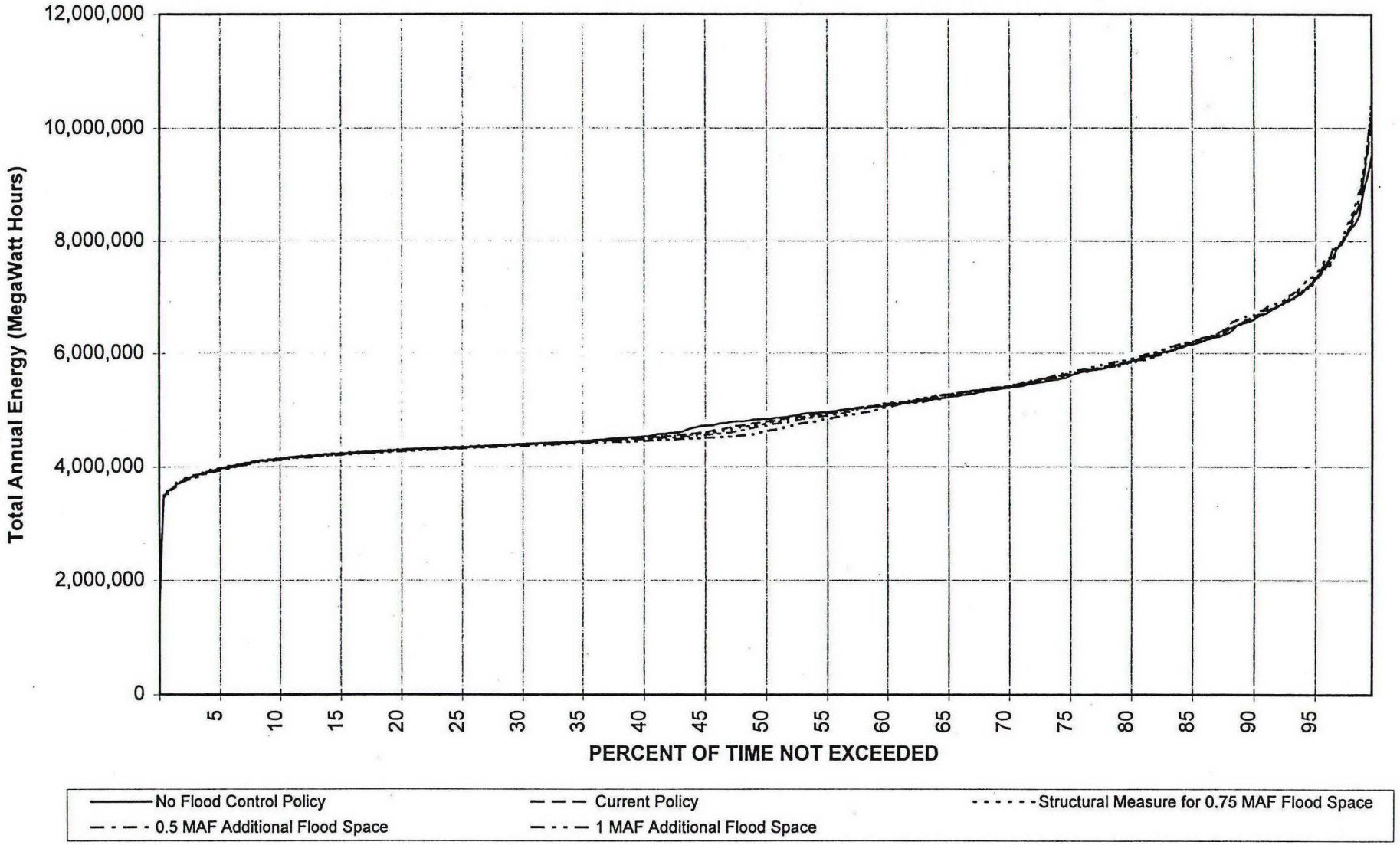


LAST UPDATED Scenario 13: 4/6/95 03:23pm Scenario 5: 4/6/95 03:26pm Scenario 6: 4/6/95 03:30pm Scenario 7: 4/6/95 03:34pm Scenario 8: 4/6/95 03:37pm

Figure D-7

Frequency Distribution Curves of Annual Total Energy Generated at Glen Canyon Dam from the 1400-Year Study Period for the Five Operational Schemes

With Year-2010 Depletion Level

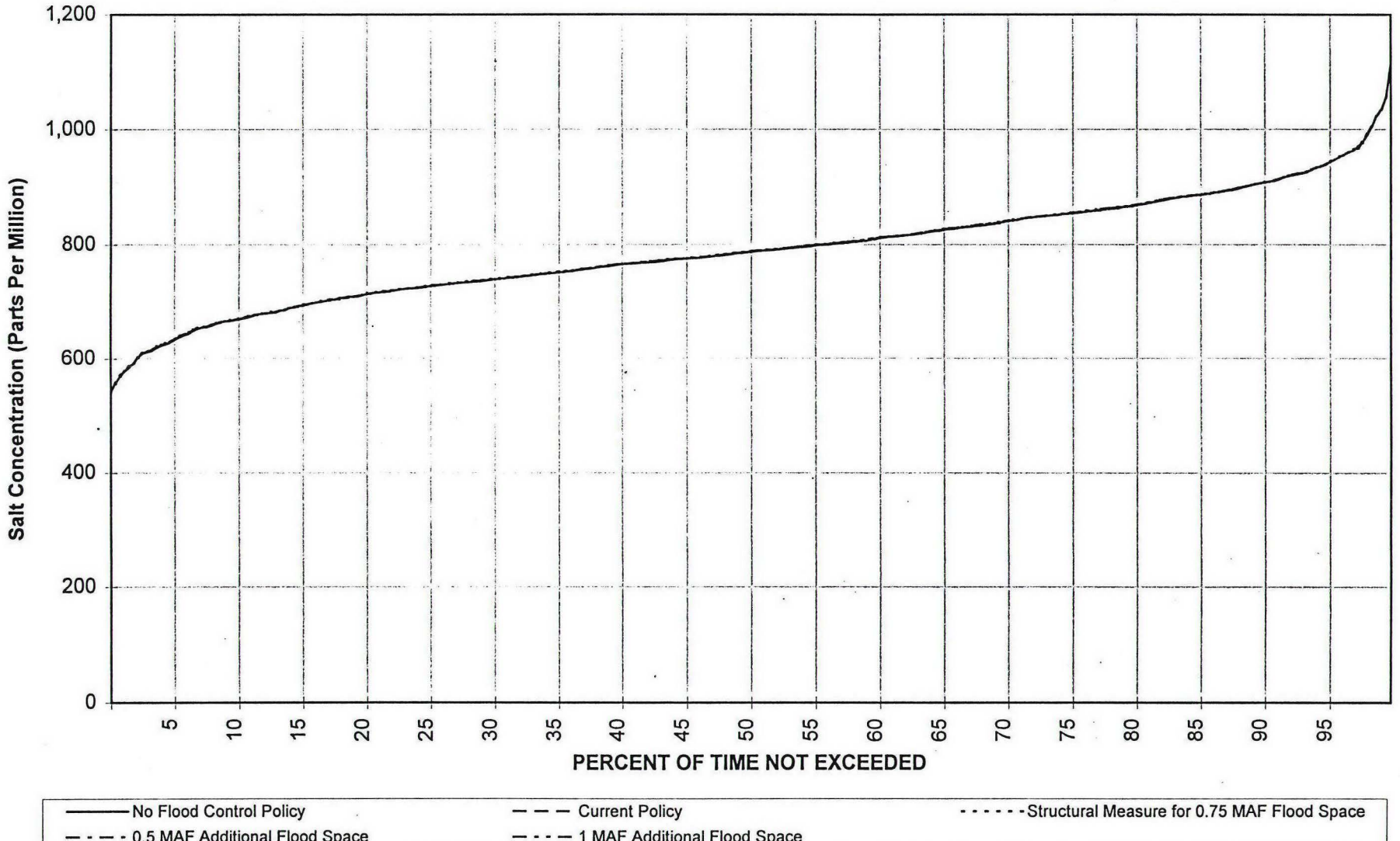


LAST UPDATED Scenario 13: 4/6/95 03:23pm Scenario 5: 4/6/95 03:27pm Scenario 6: 4/6/95 03:30pm Scenario 7: 4/6/95 03:34pm Scenario 8: 4/6/95 03:38pm

Figure D-8

Frequency Distribution Curves of Annual Salt Concentration Below Lake Mead from the 1400-Year Study Period for the Five Operational Schemes

With Year-2010 Depletion Level

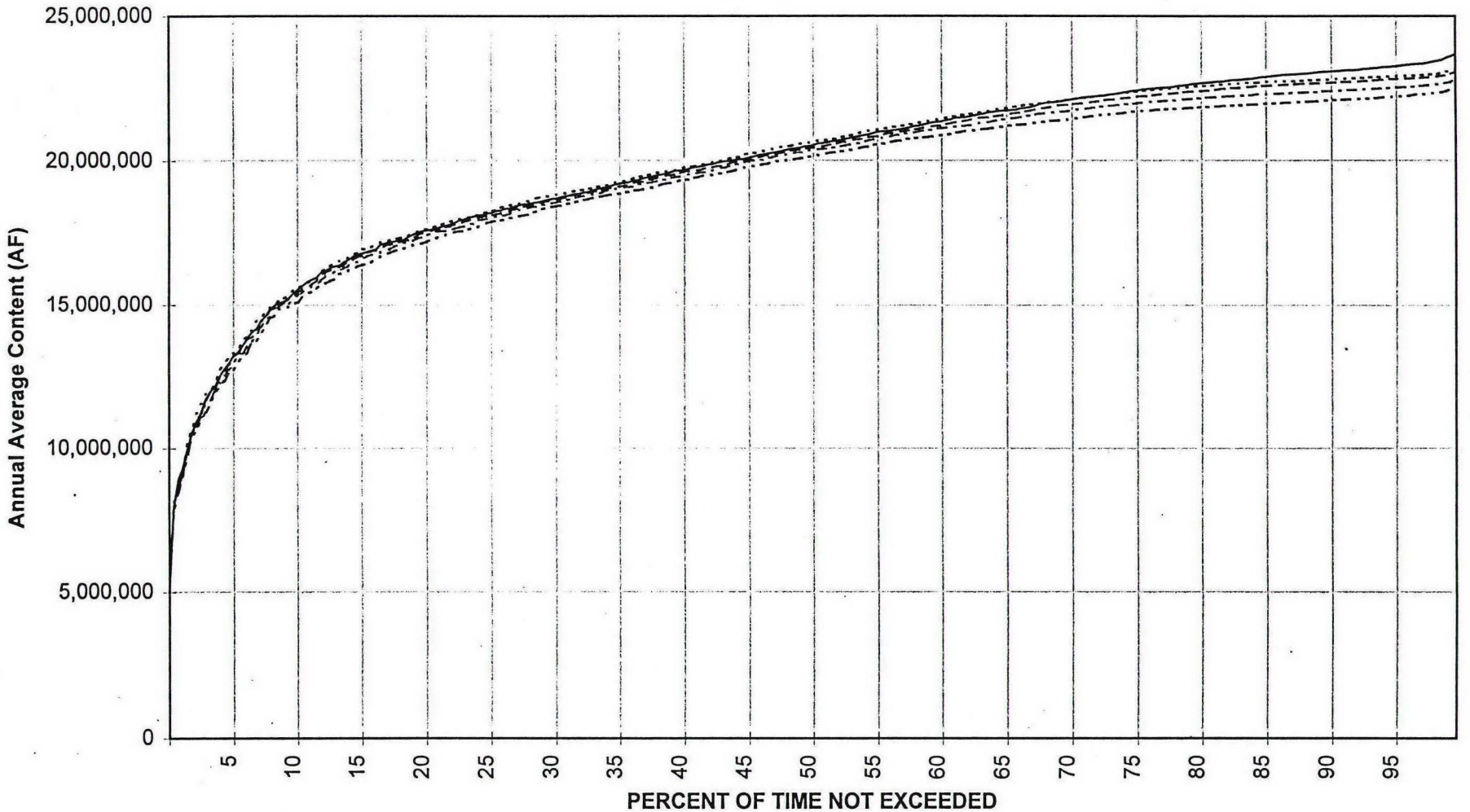


LAST UPDATED Scenario 13: 4/6/95 03:23pm Scenario 5: 4/6/95 03:27pm Scenario 6: 4/6/95 03:31pm Scenario 7: 4/6/95 03:34pm Scenario 8: 4/6/95 03:38pm

Figure D-9

Frequency Distribution Curves of Average Annual Storage Contents at Lake Powell from the 1400-Year Study Period for the Five Operational Schemes

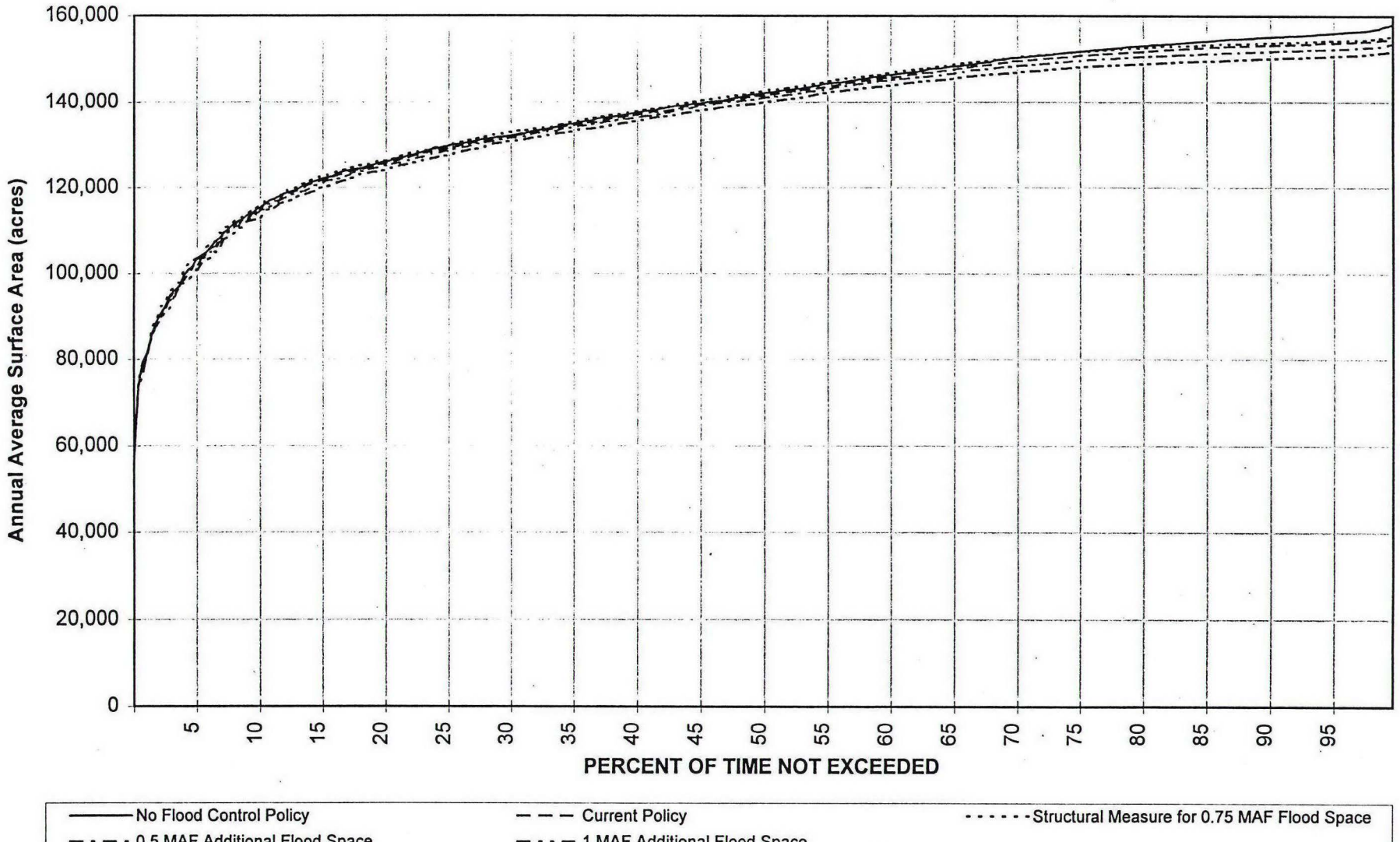
With Year-2010 Depletion Level



LAST UPDATED Scenario 13: 4/6/95 03:24pm Scenario 5: 4/6/95 03:27pm Scenario 6: 4/6/95 03:31pm Scenario 7: 4/6/95 03:35pm Scenario 8: 4/6/95 03:38pm

Figure D-10

Frequency Distribution Curves of Annual Average Reservoir Surface Area at Lake Powell in Each Year from the 1400-Year Study Period for the Five Operational Schemes With Year-2010 Depletion Level

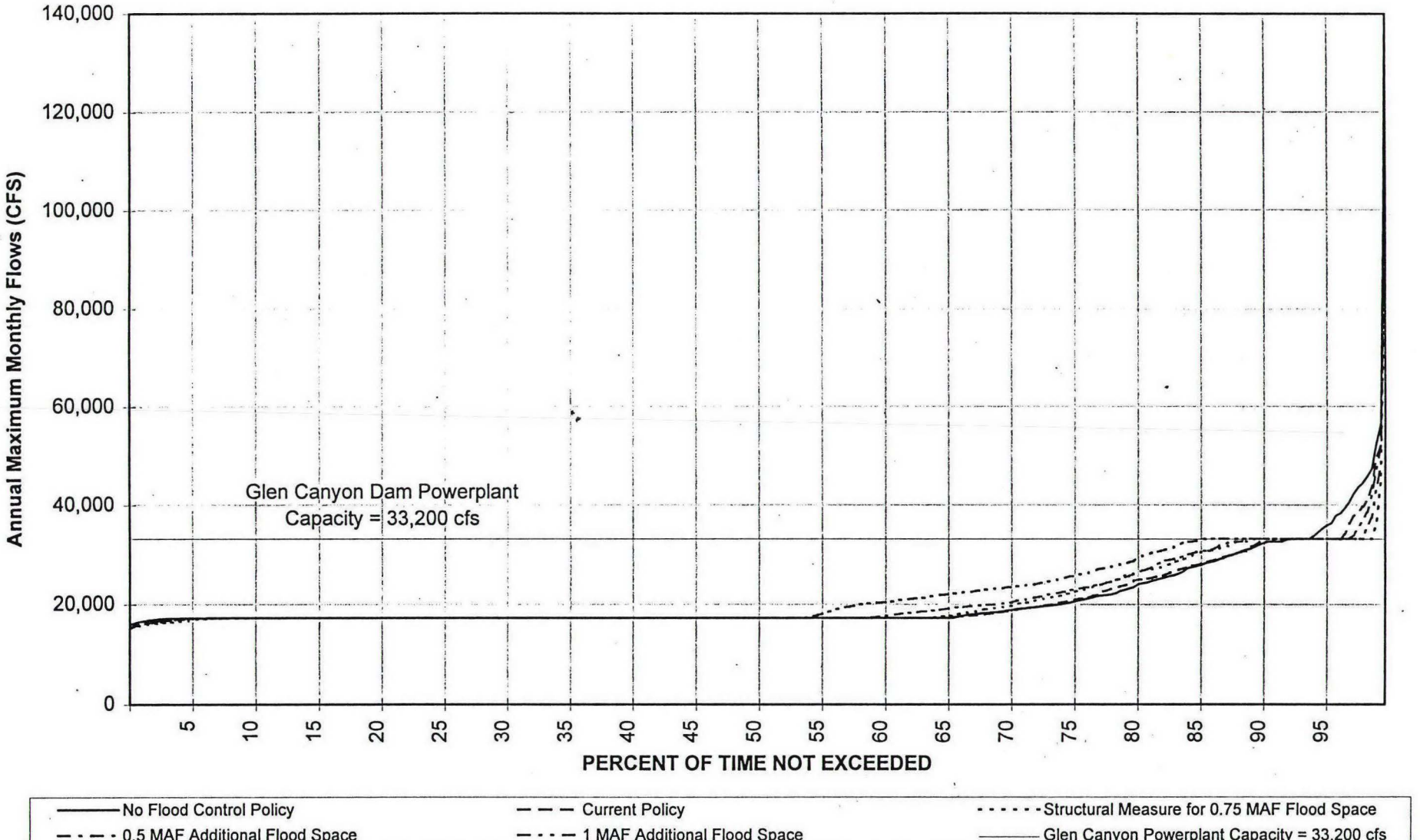


LAST UPDATED Scenario 13: 4/6/95 03:24pm Scenario 5: 4/6/95 03:28pm Scenario 6: 4/6/95 03:31pm Scenario 7: 4/6/95 03:35pm Scenario 8: 4/6/95 03:39pm

Figure E-1

Frequency Distribution Curves of Maximum Monthly Flow Below Glen Canyon Dam in Each Year of the 1400-Year Study Period for the Five Operational Schemes

With Year-2030 Depletion Level

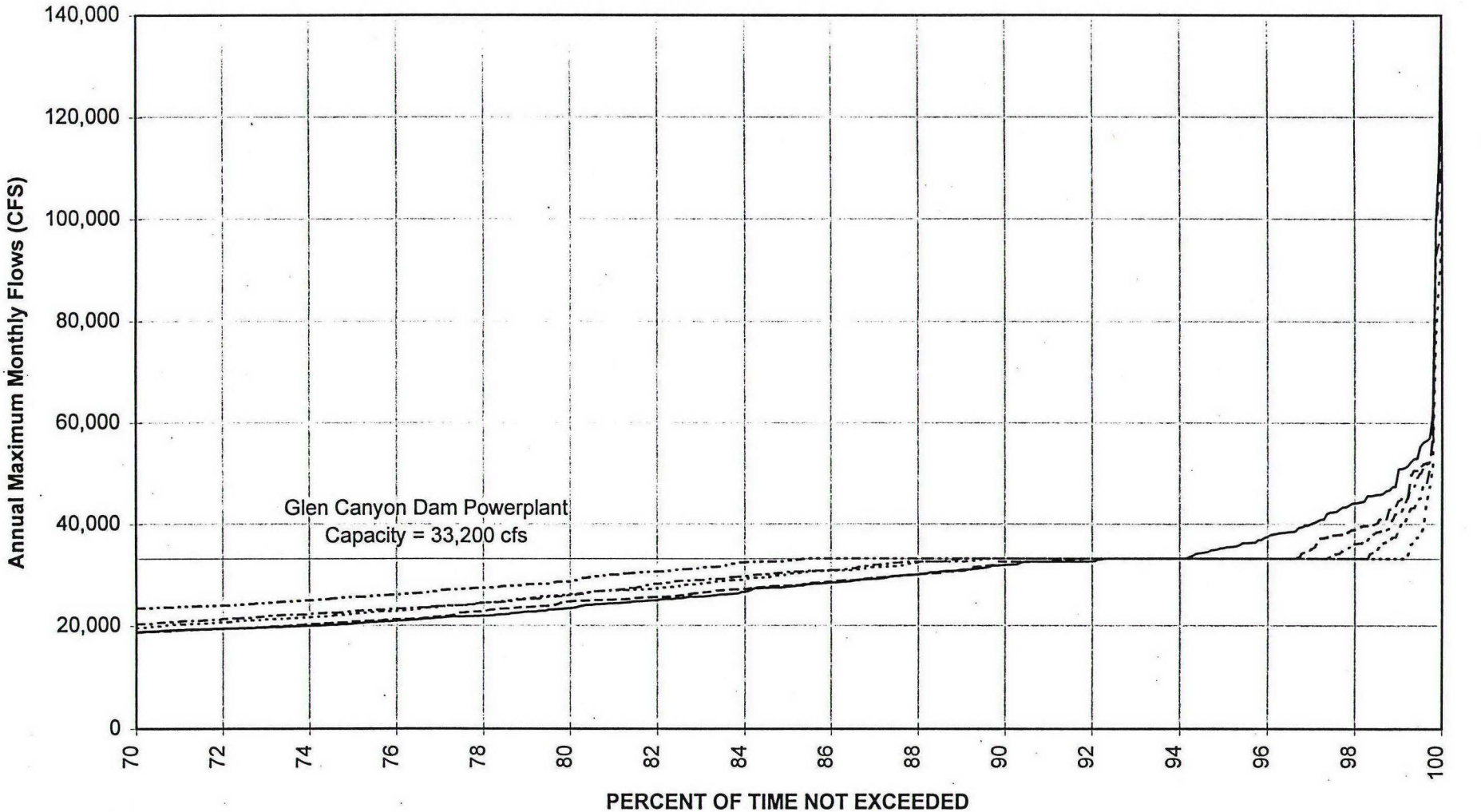


LAST UPDATED Scenario 14: 4/6/95/ 03:42pm Scenario 9: 4/6/95 03:46pm Scenario 10: 4/6/95 03:49pm Scenario 11: 4/6/95 03:53pm Scenario 12: 4/6/95 03:56pm

Figure E-2

Expanded Section of the Frequency Distribution Curves in Figure E-1 Showing the Tail Sections

With Year-2030 Depletion Level

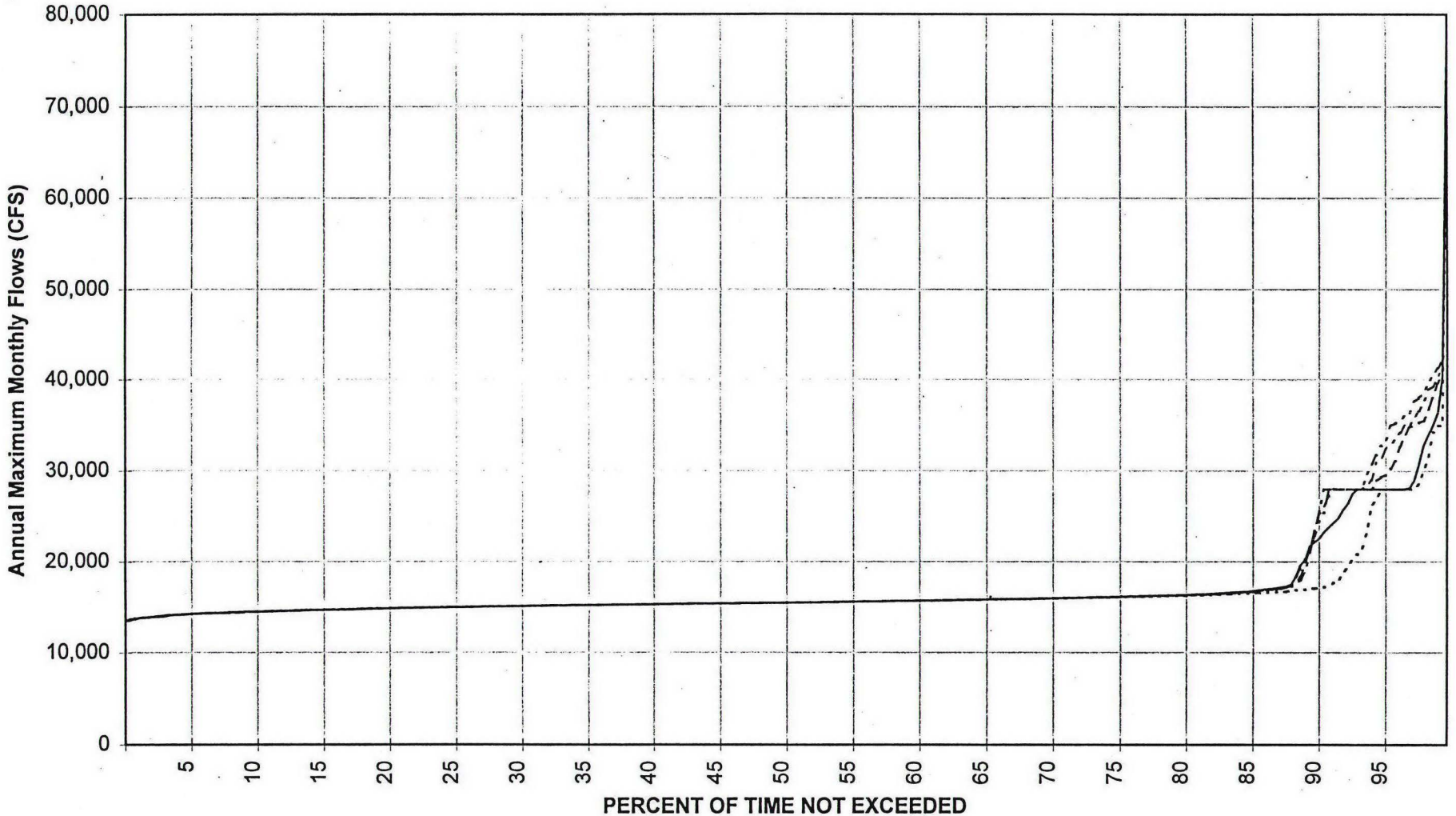


LAST UPDATED Scenario 14: 4/6/95/ 03:42pm Scenario 9: 4/6/95 03:46pm Scenario 10: 4/6/95 03:49pm Scenario 11: 4/6/95 03:53pm Scenario 12: 4/6/95 03:56pm

Figure E-3

Frequency Distribution Curves of Maximum Monthly Flows Below Lake Mead in Each Year of the 1400-Year Study Period for the Five Operational Schemes

With Year-2030 Depletion Level

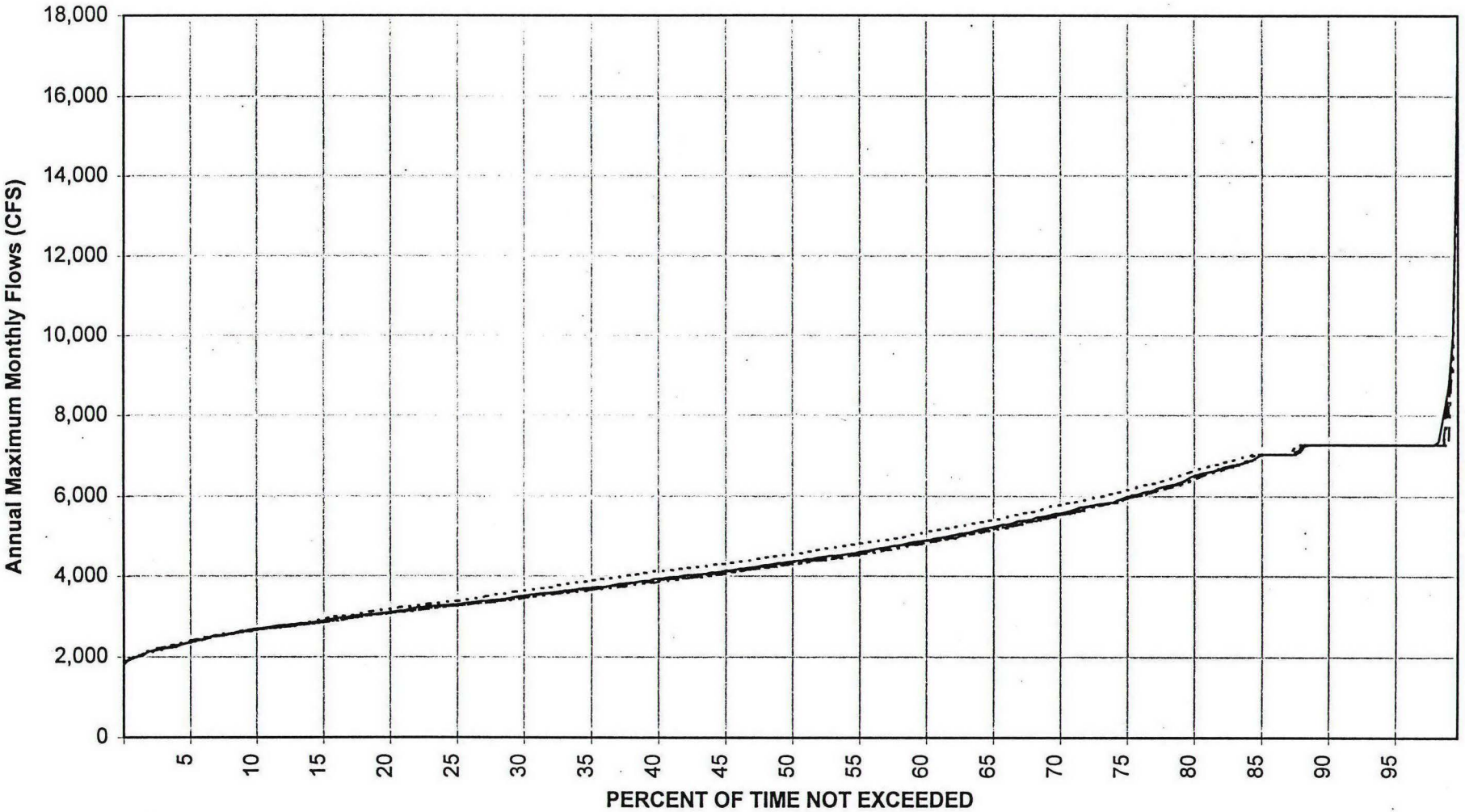


LAST UPDATED Scenario 14: 4/6/95/ 03:43pm Scenario 9: 4/6/95 03:46pm Scenario 10: 4/6/95 03:50pm Scenario 11: 4/6/95 03:53pm Scenario 12: 4/6/95 03:57pm

Figure E-4

Frequency Distribution Curves of Maximum Monthly Flow Below Flaming Gorge Dam in Each Year of the 1400-Year Study Period for the Five Operational Schemes

With Year-2030 Depletion Level

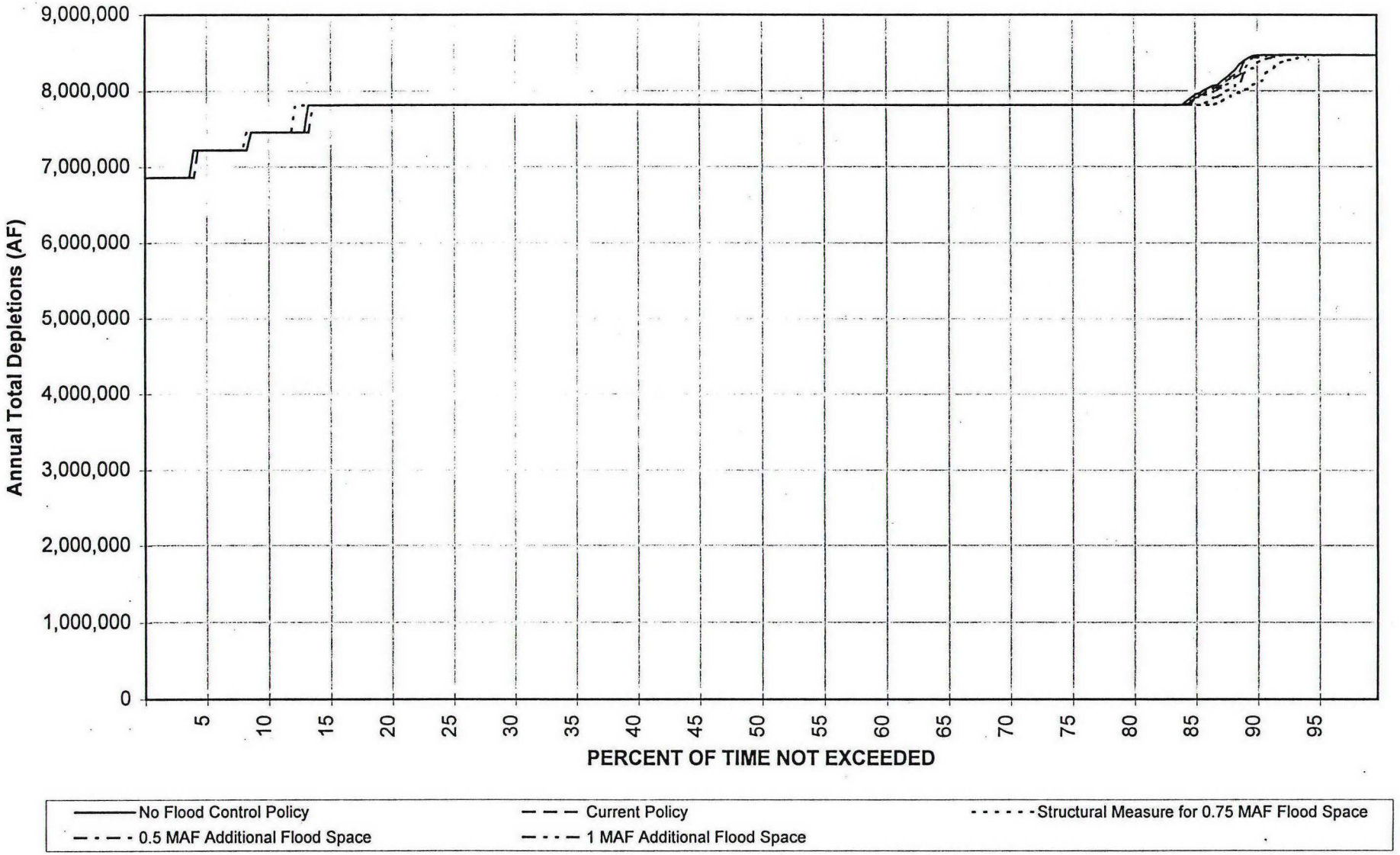


LAST UPDATED Scenario 14: 4/6/95/ 03:43pm Scenario 9: 4/6/95 03:47pm Scenario 10: 4/6/95 03:50pm Scenario 11: 4/6/95 03:54pm Scenario 12: 4/6/95 03:57pm

Figure E-5

Frequency Distribution Curves of Lower Basin Total Annual Depletions from the 1400-Year Study Period for the Five Operational Studies

With Year-2030 Depletion Level

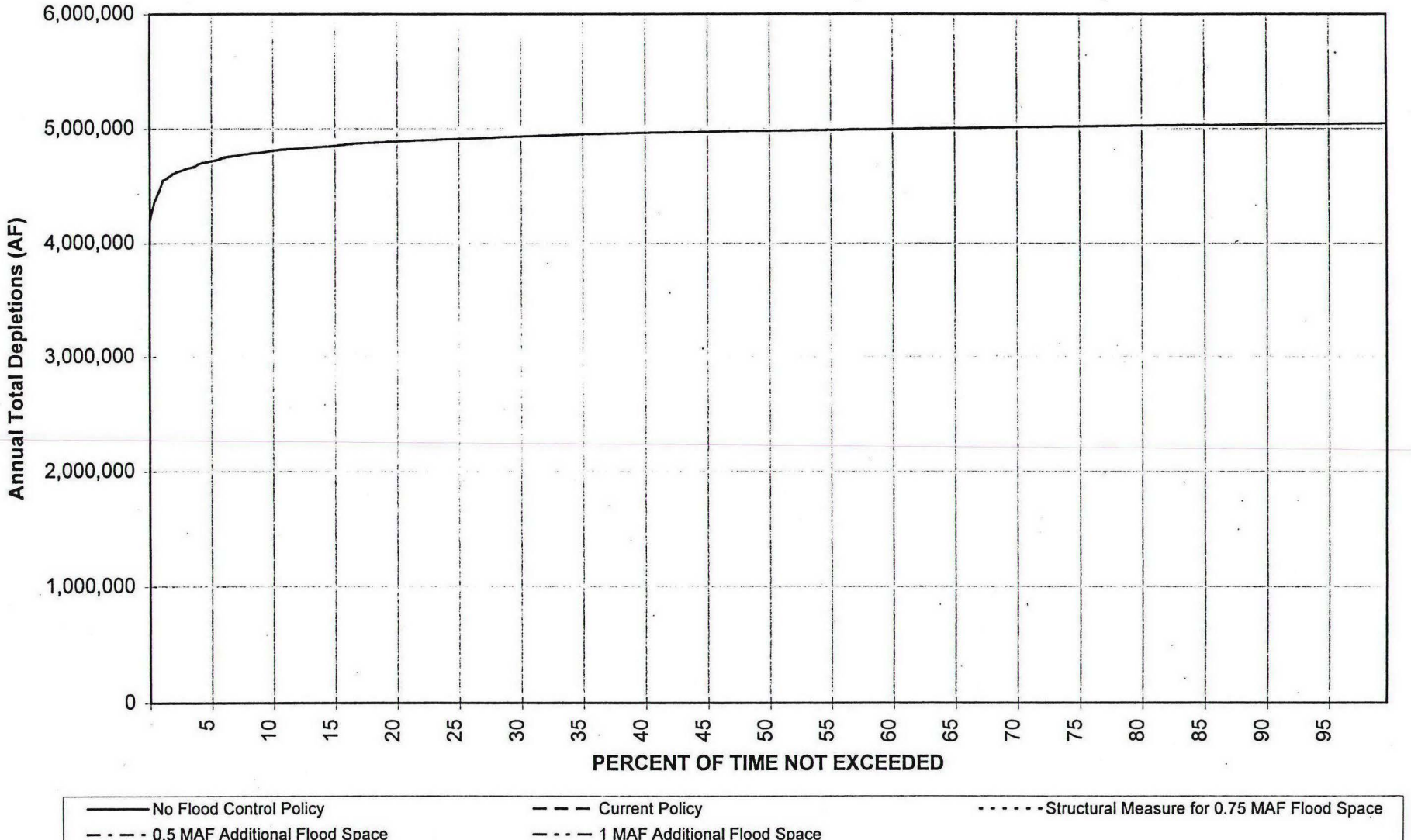


LAST UPDATED Scenario 14: 4/6/95/ 03:44pm Scenario 9: 4/6/95 03:47pm Scenario 10: 4/6/95 03:50pm Scenario 11: 4/6/95 03:54pm Scenario 12: 4/6/95 03:57pm

Figure E-6

Frequency Distribution Curves of Upper Basin Annual Total Depletions from the 1400-Year Study Period for the Five Operational Schemes

With Year-2030 Depletion Level

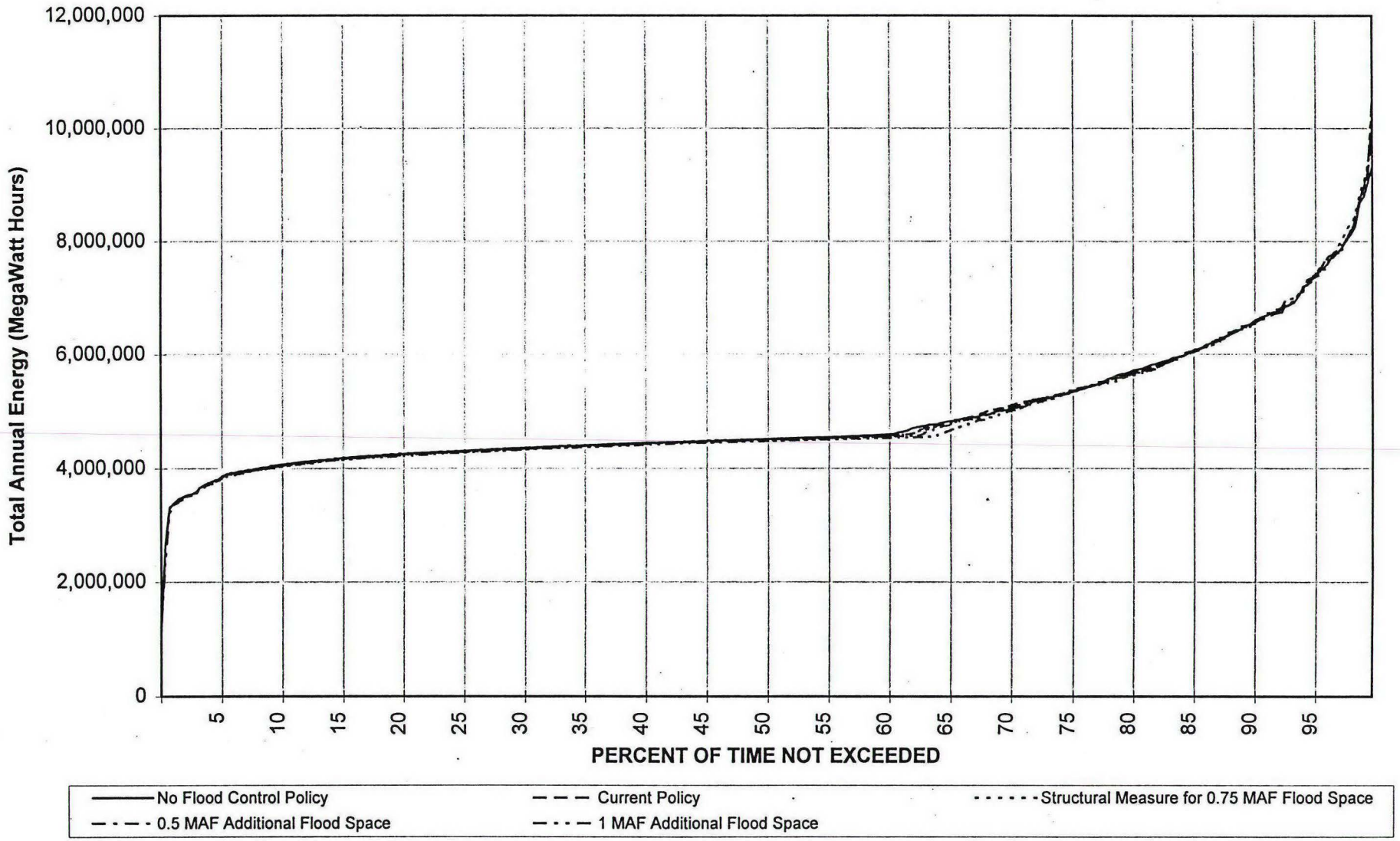


LAST UPDATED Scenario 14: 4/6/95/ 03:44pm Scenario 9: 4/6/95 03:47pm Scenario 10: 4/6/95 03:51pm Scenario 11: 4/6/95 03:54pm Scenario 12: 4/6/95 03:58pm

Figure E-7

Frequency Distribution Curves of Annual Total Energy Generated at Glen Canyon Dam from the 1400-Year Study Period for the Five Operational Schemes

With Year-2030 Depletion Level

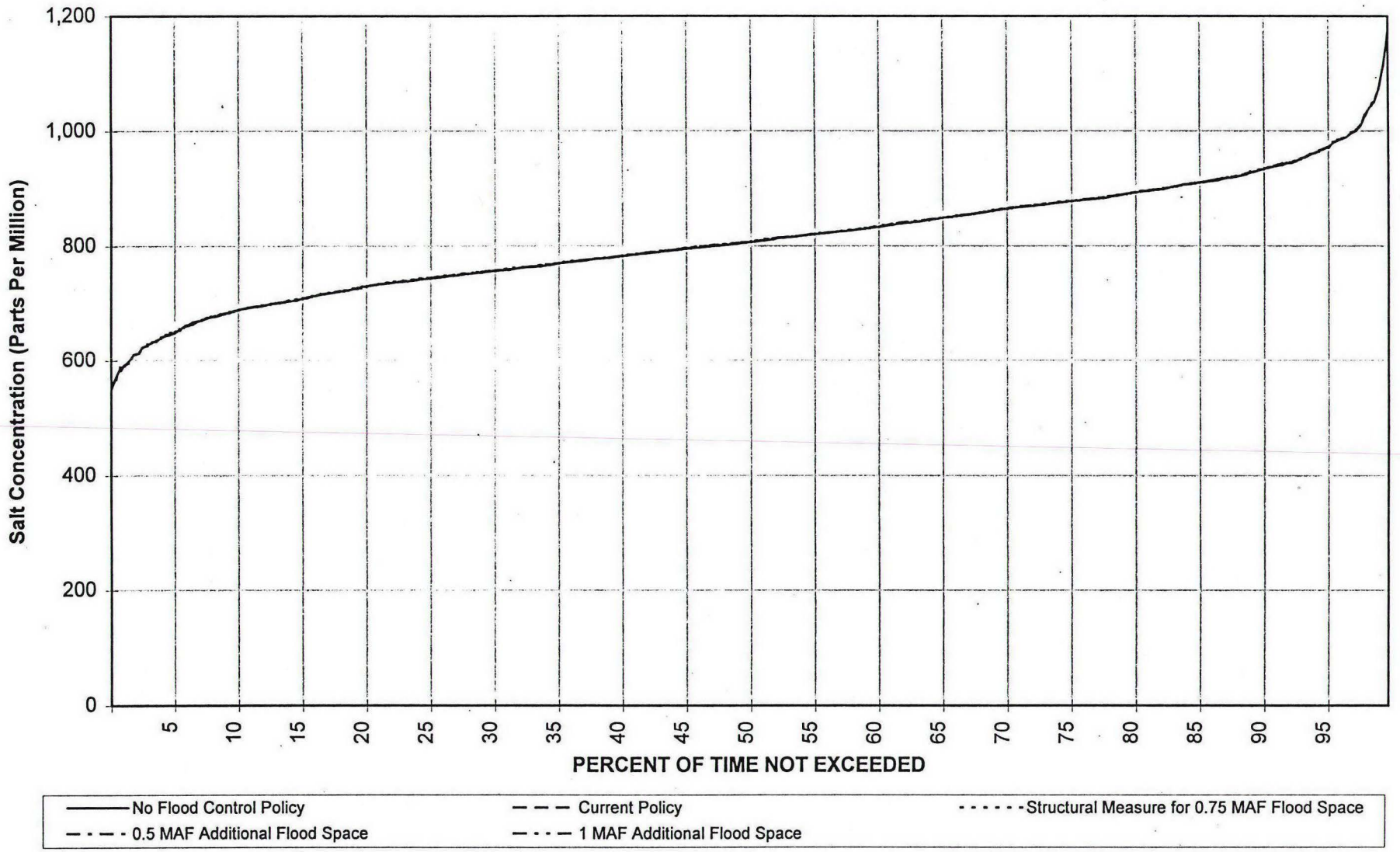


LAST UPDATED Scenario 14: 4/6/95/ 03:44pm Scenario 9: 4/6/95 03:48pm Scenario 10: 4/6/95 03:51pm Scenario 11: 4/6/95 03:54pm Scenario 12: 4/6/95 03:58pm

Figure E-8

Frequency Distribution Curves of Annual Salt Concentration Below Lake Mead from the 1400-Year Study Period for the Five Operational Schemes

With Year-2030 Depletion Level

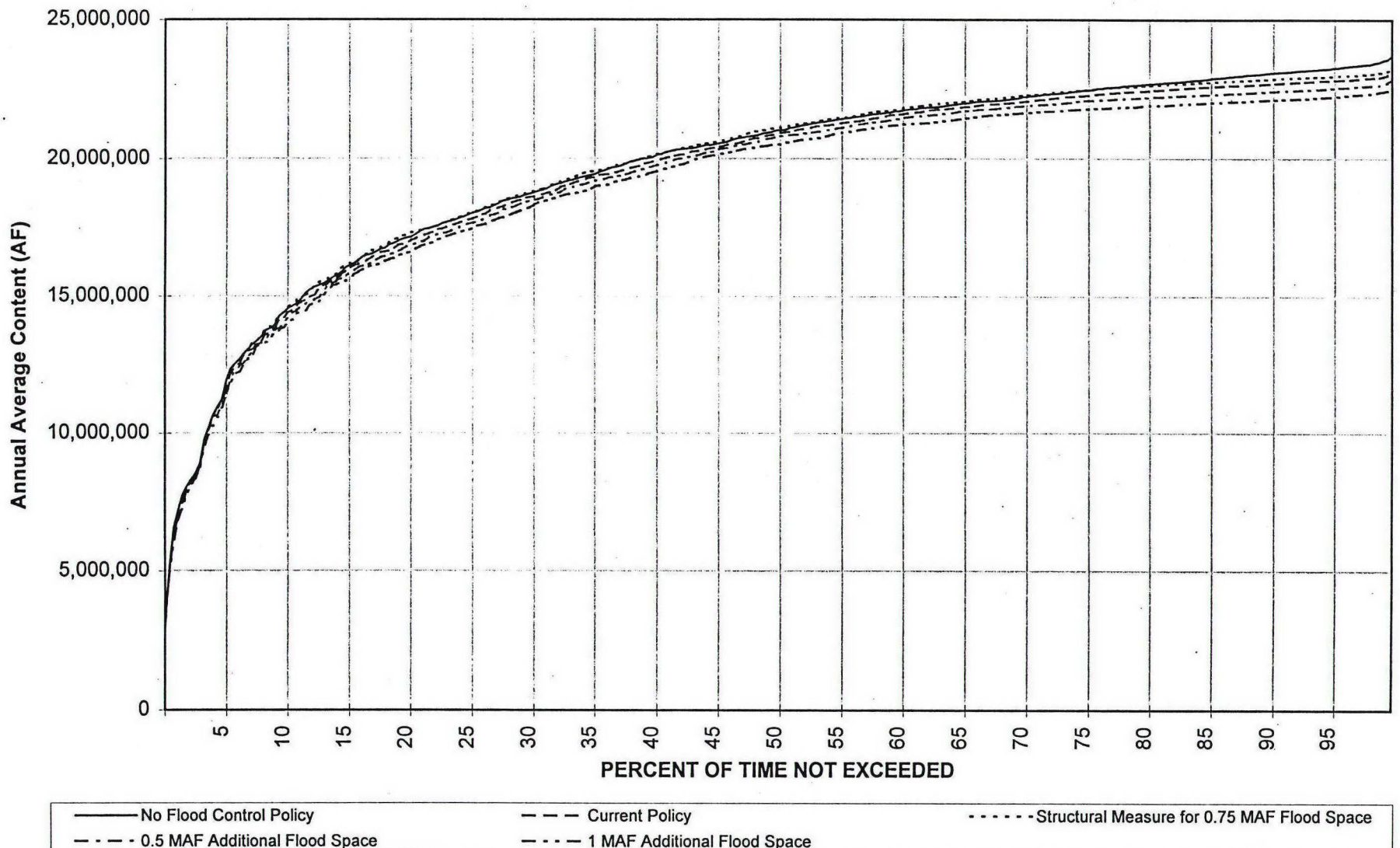


LAST UPDATED Scenario 14: 4/6/95/ 03:45pm Scenario 9: 4/6/95 03:48pm Scenario 10: 4/6/95 03:51pm Scenario 11: 4/6/95 03:55pm Scenario 12: 4/6/95 03:58pm

Figure E-9

Frequency Distribution Curves of Annual Average Storage Contents at Lake Powell from the 1400-Year Study Period for the Five Operational Schemes

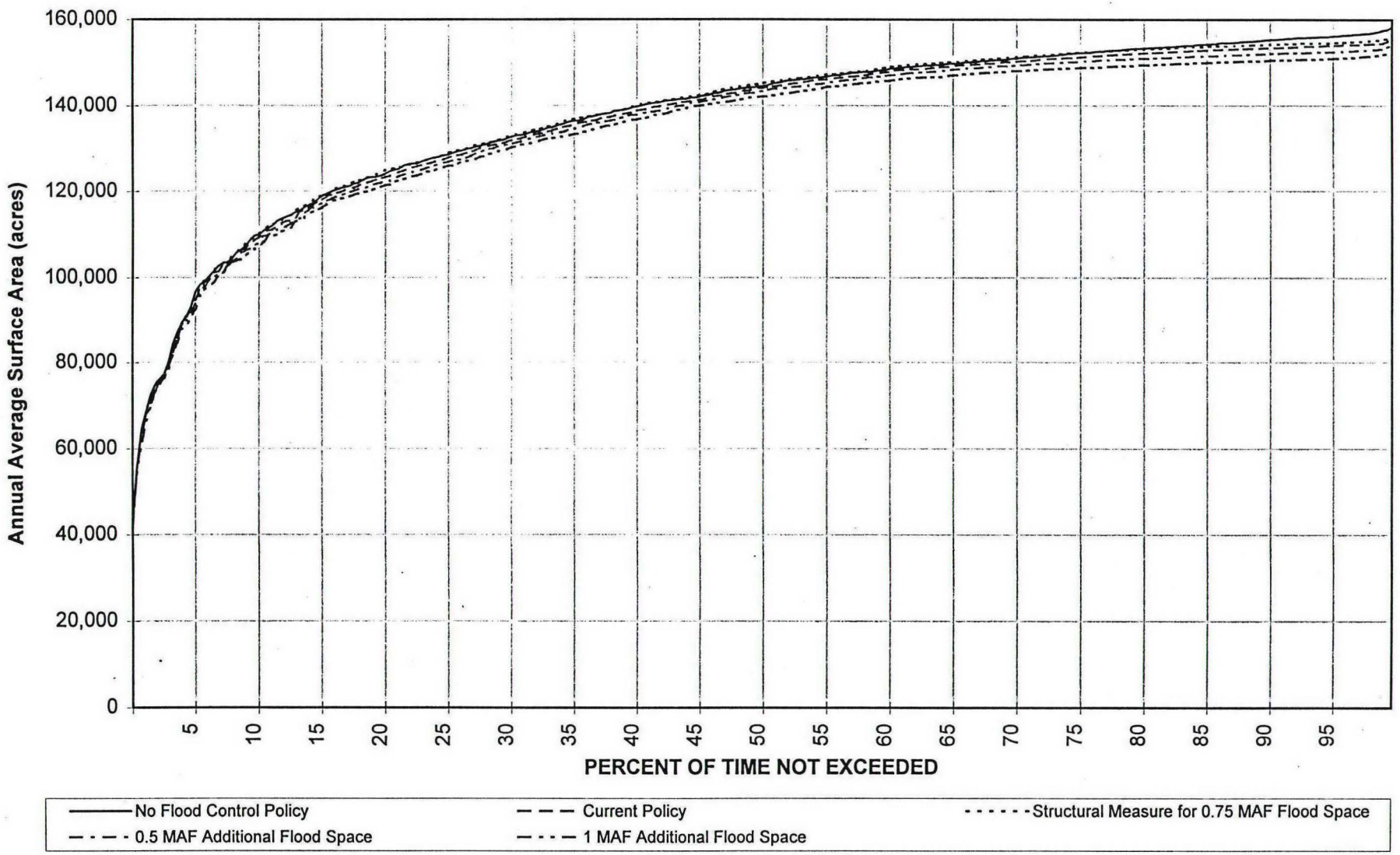
With Year-2030 Depletion Level



LAST UPDATED Scenario 14: 4/6/95/ 03:45pm Scenario 9: 4/6/95 03:48pm Scenario 10: 4/6/95 03:52pm Scenario 11: 4/6/95 03:55pm Scenario 12: 4/6/95 03:59pm

Figure E-10

Frequency Distribution Curves of Annual Average Reservoir Surface Area at Lake Powell in Each Year from the 1400-Year Study Period for the Five Operational Schemes With Year-2030 Depletion Level



LAST UPDATED Scenario 14: 4/6/95/ 03:45pm Scenario 9: 4/6/95 03:48pm Scenario 10: 4/6/95 03:52pm Scenario 11: 4/6/95 03:55pm Scenario 12: 4/6/95 03:59pm

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